

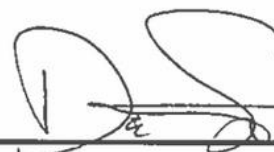
A NUMERICAL SIMULATION OF A TSUNAMI GENERATED BY A SUBMARINE LANDSLIDE, OFFSHORE PUERTO RICO

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Submitted in partial fulfillment of the requirements for graduation
with research distinction in Earth Sciences
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By

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Approved by

A handwritten signature in black ink, consisting of a large, stylized 'D' followed by a cursive 'S' and a horizontal line extending to the right.

4-14-2017

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ABSTRACT

The deepest part of the Atlantic Ocean is an area north of Puerto Rico known as the Puerto Rico Trench. Bathymetry data of the trench were acquired from the US Geological Survey and can be used to locate areas where the seafloor failed and created a marine landslide event. These events leave behind amphitheater-like cutouts in the cliff known as headscarps. In 1918 Puerto Rico experienced an earthquake and tsunami, leaving behind 116 dead. Surveyors were sent after the event to record damage and the data can be used today to study the tsunami. The tsunami is traditionally believed to have been caused directly by the earthquake. This project investigates the possibility that the earthquake caused a submarine slide instead. Previous studies have looked at different possible headscarps. However, few have used the tsunami model, GEOWAVE. This model is used best in shallow water which is applicable in this case. The simulation of the chosen slide resulted in realistic wave heights and speeds. However, not all of the simulated data agree with the reported data. Arrival times specifically are greater in the simulation than they were reported. This suggests that while a slide is a reasonable cause for the tsunami the location of the slide should be looked at further. The results from this project will be valuable those studying marine landslides in the Puerto Rico area. Knowledge of the possible tsunami risk associated with a landslide is very important from a risk assessment standpoint.

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INTRODUCTION

In 1918, Puerto Rico was struck by a 7.3 magnitude earthquake. Minutes later, the coast was hit with a tsunami approaching 5 meters in height. These events killed 116 people and caused around \$4,000,000 in damage [Reid and Taber, 1919]. The Northwest part of Puerto Rico was hit the hardest. The damage was so great that the United States' Secretary of War and the Governor of Puerto Rico requested reporters to come and document the devastation from the event. This resulted in Harry Reid and Stephen Taber recording the extent of the damage from both the earthquake and tsunami. As a result, this is one of the first modern-day tsunamis where accurate descriptions of the wave exist. Unfortunately, the earthquake data are not so well-



Figure 1: Satellite image of Puerto Rico.

known as the results of it are. There are multiple reports of where the epicenter of the earthquake is located. All the locations are found in the Mona Canyon, a tectonically active area west of Puerto Rico. The actual location of the epicenters can vary up to 40 kilometers.

These high quality reports and confusion surrounding the source have attracted scientists to study this tsunami and try to determine how it was created. Multiple papers have been published suggesting the mechanism for tsunami generation [*Hornbach et al.*, 2008; *Lopez-Venegas et al.*, 2008; *Mercado and McCann*, 1998]. Some of these claim an earthquake as the source and others look to nearby headscarps to suggest that a submarine slide was the source.

The group who believes a submarine slide to be the source has some evidence to back it up. *Reid and Taber*, [1919] document that after the earthquake it was found that two underwater cables in the Mona Canyon were broken. The repair boat found that the cables were buried under piles of sediment which suggest a slide broke them, not just the force of the earthquake. The area around the broken cables is full of visible headscarps on bathymetry data. Other studies have taken these headscarps and simulated what the slides and resulting tsunamis have looked like [*Hornbach et al.*, 2008; *Lopez-Venegas et al.*, 2008].

This study looks at a particular headscarp and models the resulting tsunami using a previously unused model, GEOWAVE. The headscarp in question is one also studied by *Hornbach et al.*, [2008] but in that study, GEOWAVE was not used. This model has been proven accurate in areas where seafloor slope is changing, as in this case [*Watts et al.*, 2003]. This study investigates whether this model will agree with the previous study or yield different results at which case the source should be revisited.

BACKGROUND

Geologic Setting

Puerto Rico sits on the Caribbean Plate. The plate is made up of several microplates that are actively moving according to GPS data [Jansma *et al.*, 2000]. These microplates are splitting apart in an East-West direction along what is called the Mona Rift. The proposed slide is on the flanks of this rift which is expanding up to 5mm a year [Lopez-Venegas *et al.*, 2008].

The lithology of the Mona Rift area was determined by a core and seismic reflection data correlated with that core. The core was drilled in the north coast of Puerto Rico, to the east of the Mona Rift. The core and reflection data show that the stratigraphy is dominated by carbonates (Figure 2) [Mondziel *et al.*, 2010]. Lopez-Venegas *et al.* [2008] show that other submarine

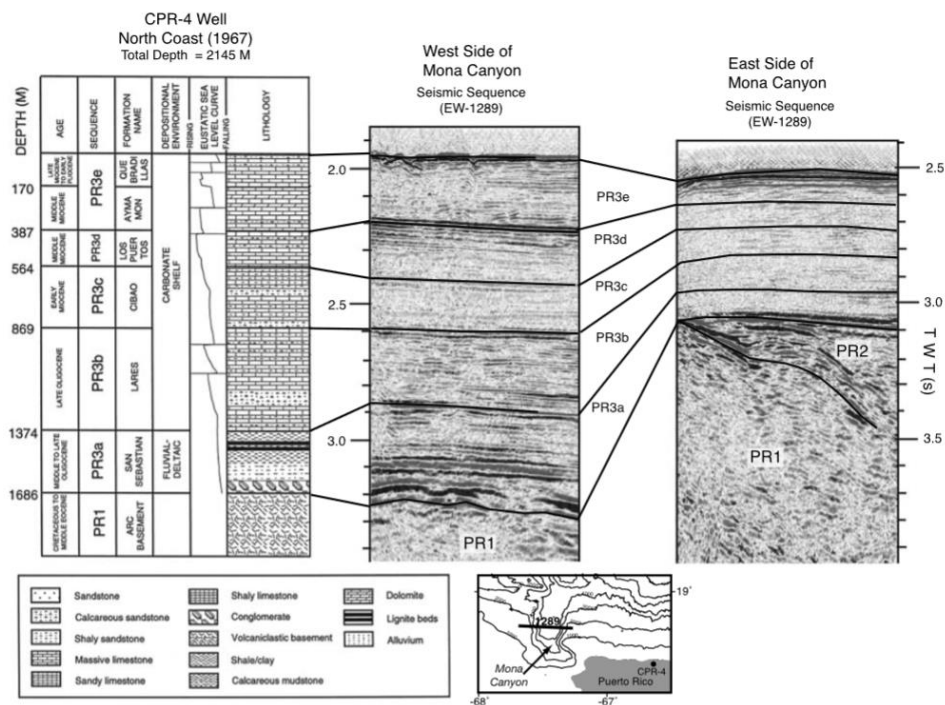


Figure 2: Interpreted core data from Briggs and Gordon [1961] correlated with seismic data interpreted by Mondziel *et al.*, [2010]. The core was taken to the east of the seismic data, which crosses the Mona Rift.

landslide events in the area involve carbonate. They claim that a weaker layer allows a block of carbonate to become displaced and sent downslope. The same scenario could have happened

with the slide in question because the stratigraphic column shows the majority of the near seafloor deposits are carbonate.

Submarine Slide Induced Tsunamis

It is often difficult to tell whether a tsunami was caused by an earthquake or a landslide. *Tappin et al.* [2008] show that many tsunamis are initially blamed on an earthquake until further research is done that reveals a submarine slide. A submarine slide causes a tsunami similarly to an earthquake. The water column responds to changes on the seafloor. Instead of fault displacement causing a change, a sliding mass adds and removes mass from the floor. As a slide

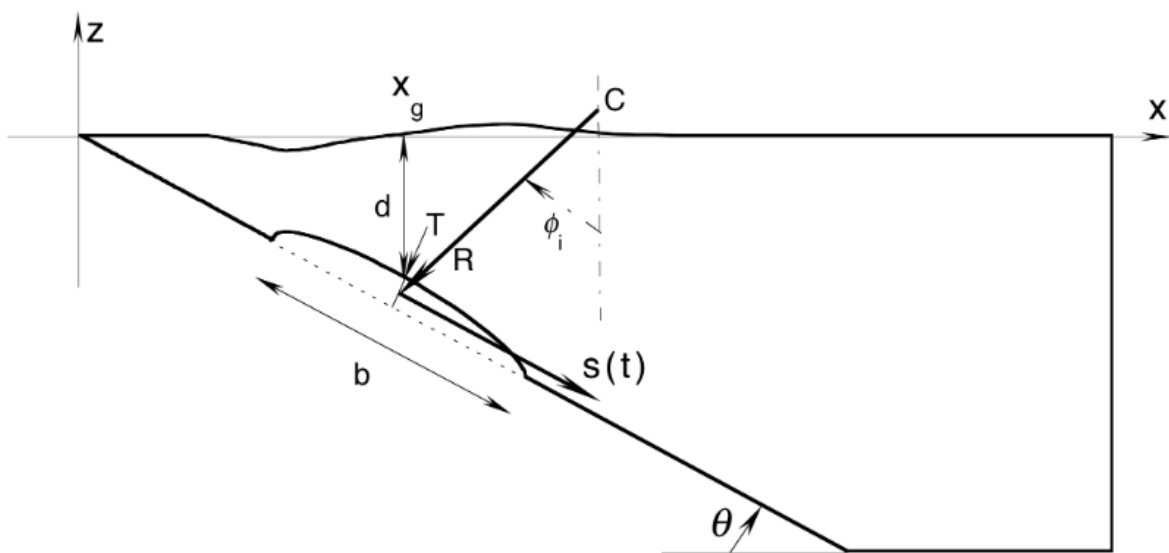


Figure 3: Diagram of how a slide of a defined thickness and length causes a disturbance on the water surface which can become a tsunami. From [Watts *et al.*, 2003].

moves down a slope it is removing mass where it was and adding mass where it is. This process is shown by Watts *et al.*, [2003] (Figure 3). Where the mass was, there is a depression in the water column where the water moved down to fill in the depression. There is a peak where the slide moves to because the new mass displaces the water.

METHODS

This project involved using bathymetry data for simulation purposes. Bathymetry data had to be collected and edited to a format that can be used with the simulator. Then inputs for the simulation must be determined and entered. The model then outputs amplitude and time maps that are used to compare the model with historical data.

Bathymetric Data

Multibeam bathymetric data were downloaded from the National Geophysical Data Center, a branch of the National Oceanic and Atmospheric Administration [Taylor *et al.*, 2008]. These data were originally collected in two separate surveys and compiled after collection. The first, in 2006, was done on the *Ron Brown* and the second, in 2007, on the *Nancy Foster*. The reason for collecting the data was for tsunami simulation in the Pacific Marine Environmental Laboratory. The grid spacing is 1/3 arc second which is approximately 10 meters. The horizontal datum is World Geodetic System 1984 and the vertical datum is Mean High Water.

These bathymetric data were collected and formatted with the needs of the Pacific Marine Environmental Laboratory's tsunami simulation in mind. Because of this the downloaded data needed to be manipulated before they could be used with GEOWAVE. The major limiting factor with GEOWAVE is the size of the grid that it can read which is only 800 by 800 cells. Reducing the grid size was done in two ways. The first method was to reduce the scope of the bathymetric grid to just the Northwest portion that contained the slide. The second part was to increase the cell size until the area of study was reduced to less than an 800 by 800 grid (Figure 4A).

Slide Interpretation

Around the area of Mona Canyon are multiple headscarps each of which could have triggered a tsunami. Hornbach *et al.* [2008] make a strong case for a particular headscarp to be

related to the 1918 earthquake. The study selected a headscarp located at 18.46° N, -67.33° W at

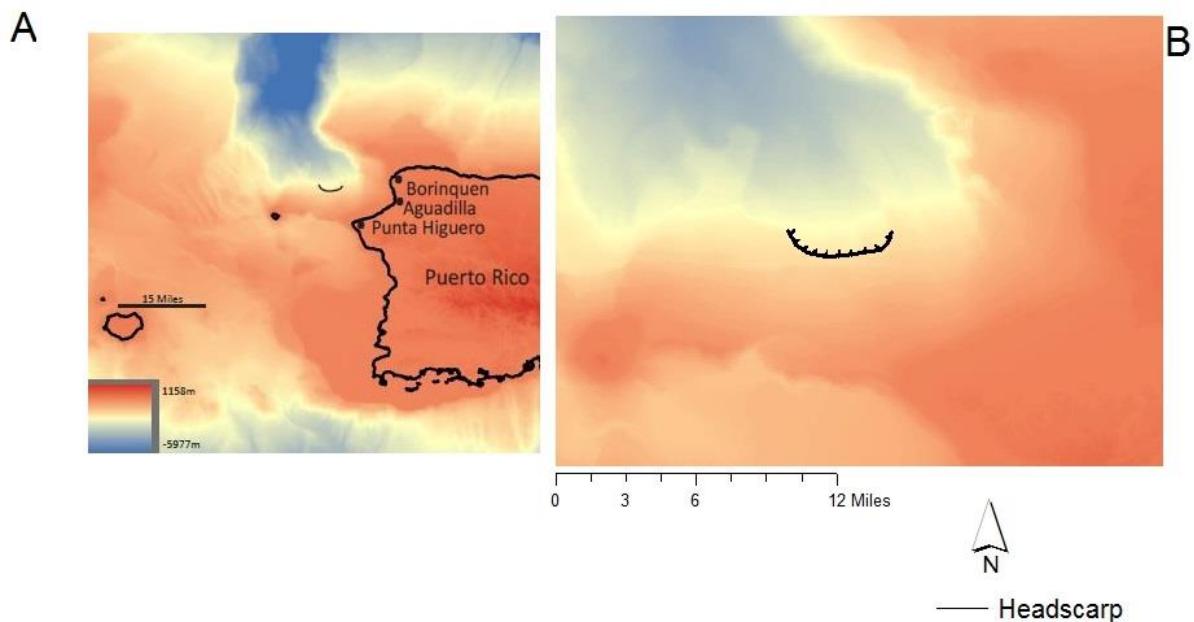


Figure 4: (A) Bathymetric map after ArcGIS processing to reduce the grid size down to 800 by 800. The headscarp to be investigated is shown by a black line. (B) Detail in map on area of headscarp.

a water depth of around 1300m (Figure 4). This headscarp was chosen is due to its proximity to the submarine cables that were broken. Broken cables have been linked to submarine slides in the past [*Krause et al.*, 1970]. Some cables were found buried under piles of sediment [*Reid and Taber*, 1919]. Because these cables were found just north of the headscarp *Hornbach et al.* [2008] chose this as the site of failure. The amount of sediment also shows that the slide volume was probably on the kilometer scale which matches the selected scarp.

According to the bathymetry data the slide has a width of 9km and a thickness of 0.2km. These are maximum dimensions based on the assumption that the headscarp failed in a single event. The length of the slide is more difficult to determine just from the bathymetry data. *Hornbach et al.* [2008] estimated a total slide volume of 6km^3 by using Gaussian functions.

GEOWAVE requires the length, width, and thickness of the slide. In order to be consistent with Hornbach et al's 6km³, 3.33km was used for the length.

Numerical Simulation

GEOWAVE is a model that simulates tsunami propagation and inundation using nonlinear Boussinesq equations [Watts *et al.*, 2003]. GEOWAVE relies on a long wave propagation model called FUNWAVE to implement those equations. This model has several advantages because of the nonlinear Boussinesq equations. Most models' horizontal wave velocity is controlled by depth. This is not the case with FUNWAVE. It is typical for waves' horizontal velocities not to correspond to depth when they move up slope, as in this case.

GEOWAVE can create tsunamis from a variety of sources including: earthquakes, translational submarine slides, rotational submarine slides, and subaerial slides. For the tsunami in question this study will use the translational submarine slide as a source as this is most similar to what Hornbach *et al.* [2008] performed. GEOWAVE simplifies the process of a submarine slide in a few ways. The model assumes the mass is a solid body, moving in a straight line at a constant angle. To determine slide speed and acceleration Watts *et al.*, [2003] utilized experimental data to create several equations. The coefficients found in these equations agree

$$(1a) s(t) = s_o \ln \left[\cosh \left(\frac{t}{t_o} \right) \right]$$

$$(1b) a_o \cong 0.30g \sin \theta$$

$$(1c) u_t \cong 1.16 \sqrt{bg \sin \theta}$$

$$(1d) s_o \equiv \frac{u_t^2}{a_o} \cong 4.48b$$

s(t)=distance travelled at time t (m)

s_o=distance travelled at previous step (m)

t=time (s)

t_o=time of previous step (s)

a_o= initial acceleration (m/s²)

g=acceleration due to gravity (m/s²)

θ=slope angle (degrees)

u_t=theoretical terminal velocity (m/s)

$$(1e) \ t_o \equiv \frac{u_t}{a_o} \cong 3.87 \sqrt{\frac{b}{g \sin \theta}} \quad b = \text{landslide body length (m)}$$

with previous research regarding slide motion. In order for GEOWAVE to simulate mass movement, some inputs regarding the slide are required (Table 1). Before any numerical inputs occur, one must supply an ascii grid of the bathymetry. The information associated with this grid

Table 1

| | |
|---|--------|
| Initial x-axis mass failure center (decimal degrees) | -67.33 |
| Initial y-axis mass failure center (decimal degrees) | 18.46 |
| CCW angle of north in degrees from grid top (degrees) | 0 |
| CCW angle of failure in degrees from north (degrees) | 50 |
| Initial depth of the middle of slide (m) | 1430 |
| Mean slope along failure plane (degrees) | 7 |
| Initial slide length during failure (m) | 3333 |
| Maximum initial slide thickness (m) | 200 |
| Maximum initial slide width (m) | 9000 |
| Slide bulk density (kg/m ³) | 1850 |

Table 1: Inputs used in GEOWAVE to simulate a translational submarine slide adapting information from *Hornbach et al.* [2008].

will determine the format of the coordinates that are entered for the slide location. These can be in meter, feet, longitude and latitude, or in this case, decimal degrees. The slide direction is interpreted from the bathymetry data. It was found by taking the location of the slide and determining which direction had the steepest slope. This slope was found to be around 7° which

was found by putting the bathymetry data into ArcGIS. This result for slope along failure plane agrees with *Hornbach et al.* [2008] as they determined the same number. ArcGIS was used to find the depth of the failure as well. The length, width, and thickness were all adapted from *Hornbach et al.* [2008]. Those authors reported the width and thickness as well as the total volume as 6 km^2 . In order to maintain the same volume, the length had to be made 3333 m in GEOWAVE. The bulk density that was used in the *Hornbach et al.* [2008] study was not disclosed. Instead 1850 kg/m^3 was used because that is the value assumed in the equations from *Watts et al.*, [2003].

Once the source parameters are set GEOWAVE calls FUNWAVE to begin the tsunami simulation. The simulation is made up of steps each of which take 0.209 seconds. It ran for 2000 steps which represents about seven minutes of simulation time. This time was chosen because it was enough time for the wave to reach the shore but not enough time for the wave to interact with the grid boundaries and interfere with the results.

Data interpretation

Information about the 1918 tsunami comes from eyewitness reports of the event. The three location that have the most complete information are Borinquen, Aguadilla, and Punta Higuero. Reports indicate both the arrival time after the initial earthquake and the wave height. The reports from Borinquen and Punta Higuero come from the area's lighthouse keepers so wave heights are taken from the area around each lighthouse [*Reid and Taber*, 1919].

One output of GEOWAVE is a maximum wave amplitude map (Figure 5). This map is used in determining the maximum wave height at the three location. Bathymetry resolution can create error in wave amplitude when the wave reaches the shore [*Hornbach et al.* 2008]. To account for this, five values were taken along the shore at each location. At Punta Higuero the

cells are centered on the lighthouse. Figure 5c shows that wave heights are high in the entire area. However, for the other two locations, the points are not centered. In Borinquen the majority

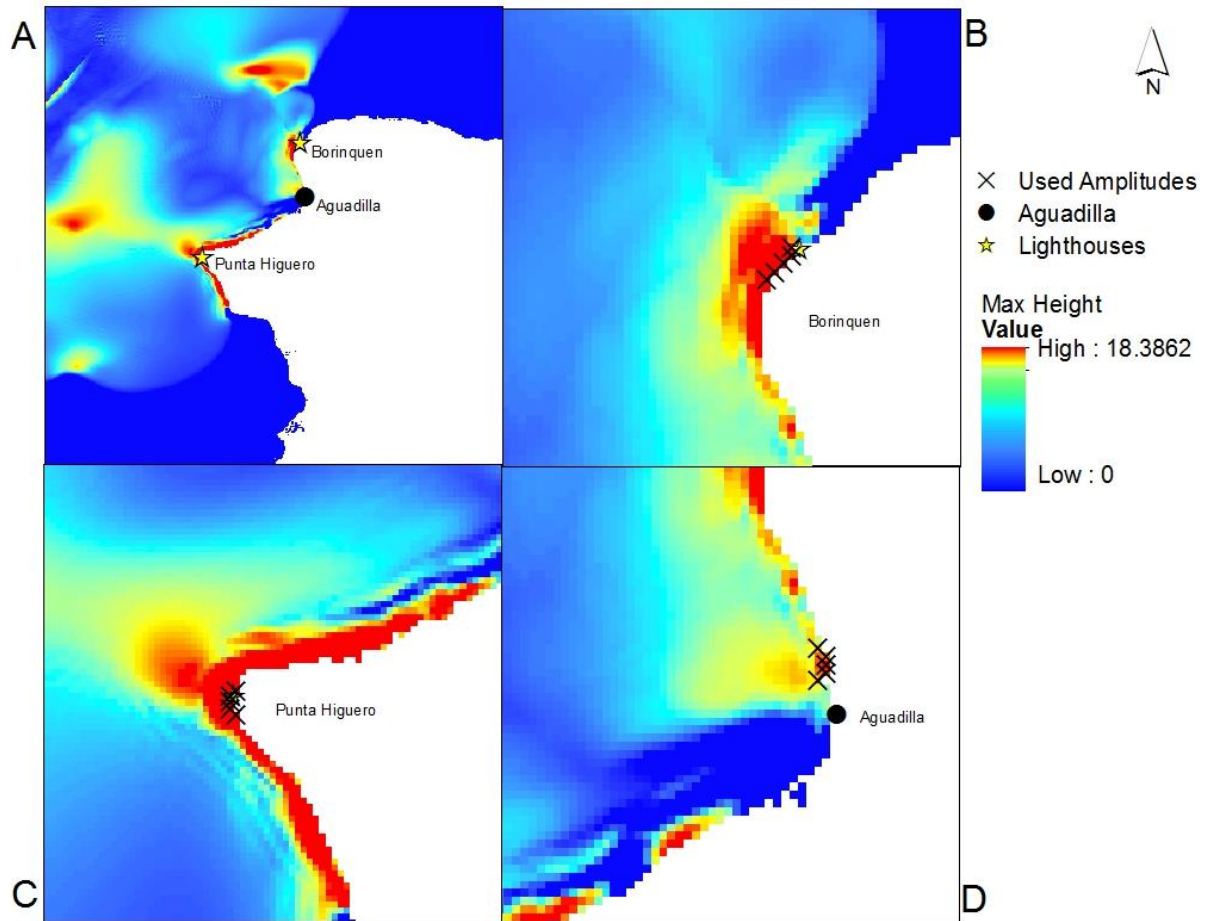


Figure 5: (A) Wave heights for the whole Northwest region of Puerto Rico. The three areas with eye witness reports are marked. (B) Wave height map of the Borinquen area. Cells used to determine average wave height are marked. (C) Wave height map of the Punta Higuero area. Cells used to determine average wave height are marked. (D) Wave height map of the Aguadilla area. Cells used to determine average wave height are marked.

of height is on the West side of the lighthouse. The lighthouse is used as the East end of the line of cells to determine the average. For Aguadilla there is a distinct area with high wave height. This area was used in the calculation. While five values do not make a large sample size it does cover a wide area. Those five points span about 2,000 feet of shoreline. Adding any more would make the local reports less useful because the wave height reports were for local areas, not

regions of the coast. Tables 2 and 3 detail the results of the simulation compared to the eye witness reports at the three location.

This simulation in GEOWAVE produced maps to show how the current wave is behaving for every ten seconds of simulation time. These maps were used to determine when the waves arrived at the three locations. The reports from *Reid and Taber*, [1919] span a wide range of times.

RESULTS

Simulation Results

The relevant outputs of the simulation include a maximum wave amplitude map and time step maps showing the current wave behavior every ten seconds for seven minutes. These are

Table 2.

| Location | Reported Arrival | Simulated Arrival |
|---------------|------------------|-------------------|
| Borinquen | 0min-3min | 4min 53sec |
| Aguadilla | 4min-7min | 5min 25sec |
| Punta Higuero | >3min | 5min 14sec |

Arrival results of the GEOWAVE simulation with the reported values from *Reid and Taber*, [1919] at Borinquen, Aguadilla, and Punta Higuero. Defined as the point of lowest wave height or during maximum drawdown.

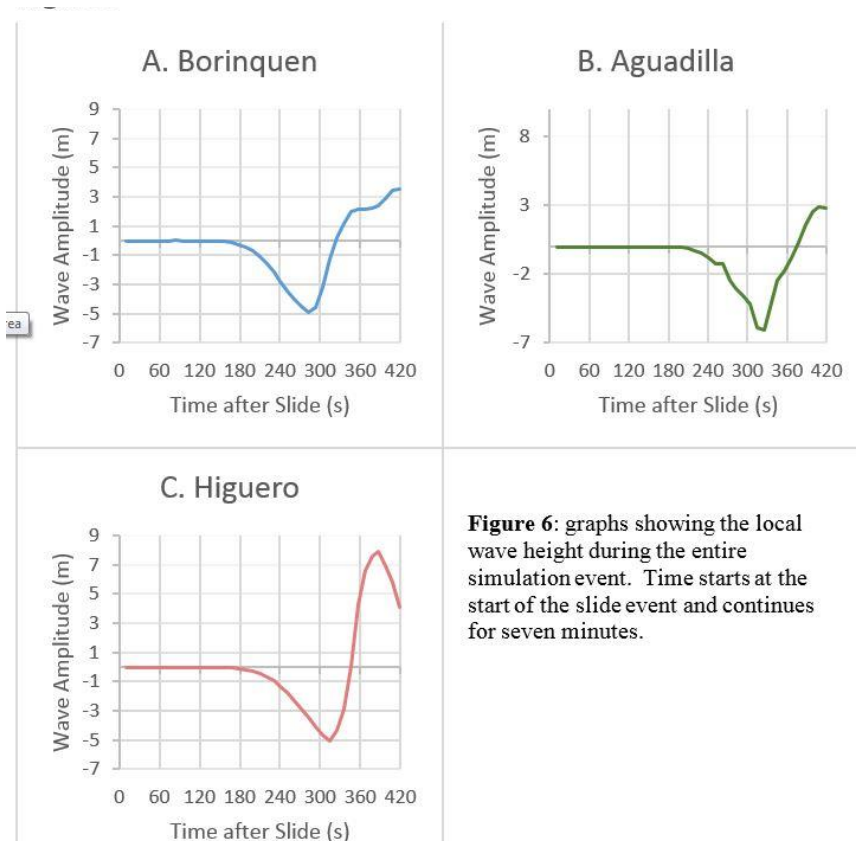


Figure 6: graphs showing the local wave height during the entire simulation event. Time starts at the start of the slide event and continues for seven minutes.

used to determine the properties of the wave as it arrived at the three study locations. The time step maps were used to create graphs for each location to track local wave height during the entire seven-minute simulation (Figure 6). The amplitudes in these graphs are different than the amplitude map values for two reasons. First, unlike the amplitude data, only one point was used for each, not an average of points. This is because the purpose of these graphs was to determine arrival time, not amplitude. Second, the values are taken further off shore than the amplitude values. The reason for this is that the water moved out before coming inland. This phenomenon is known as drawdown. This extends the shore and gives some points near the shore an undefined value for amplitude during this period.

These graphs were used to determine the approximate arrival times of the wave. The

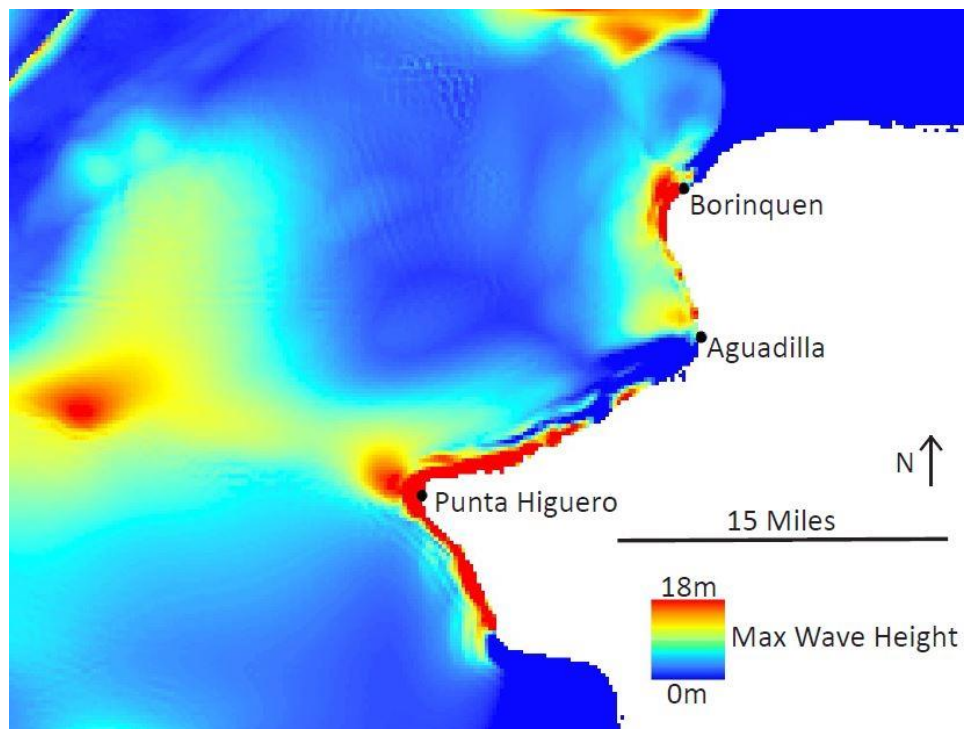


Figure 7: Map showing the maximum amplitude recorded by each cell during the entire simulation. The three study locations are marked.

arrival of the wave is defined as the lowest wave height or the time of maximum drawdown.

These results are found in Table 2 and are compared to the historical results from *Reid and Taber* [1919]. The graphs make it apparent that all three locations exhibit the drawdown trait.

The other wave property we can compare to historical records is wave height.

Fortunately, GEOWAVE outputs a map that shows the maximum amplitude recorded by each

Table 3

| Location | Reported Height | Simulated Height |
|-----------------|------------------------|-------------------------|
| Borinquen | 4.5m | 5.41m +/- 1.02m |
| Aguadilla | 2.4m-3.4m | 2.77m +/- 0.36m |
| Punta Higuero | >5.2m | 11.17m +/- 1.89m |

Height results of the GEOWAVE simulation with the reported values from *Reid and Taber*, [1919] at Borinquen, Aguadilla, and Punta Higuero. Determined by the integrated max amplitude map.

cell during the simulation (Figure 7). This was used to find the height of the wave when it arrived in each location. Results are shown in Table 3.

DISCUSSION

Are the Results Reasonable?

Wave heights ranged from 2.5m to 13m upon arrival. These wave heights are well within the realm of possibility considering some of the largest tsunamis in history have had heights well over 100m [*Mader and Gittings, 2002*]. These mega-tsunamis are normally caused by earthquakes. To compare this simulation to real world tsunamis it would be best to limit comparison to submarine landslide derived waves. One of the most devastating tsunamis attributed to a submarine slide is the 1998 Papua New Guinea tsunami where wave heights

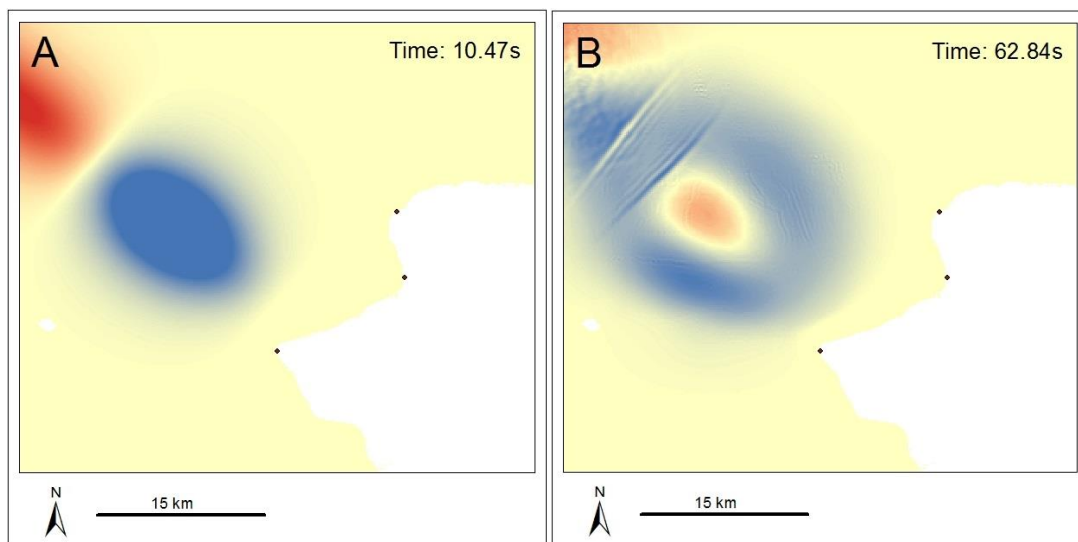


Figure 8: (A) Map showing the wave soon after the slide. The crest of the wave is not yet present. (B) Map showing the wave immediately after the crest of the wave develops.

reached 15m [*Geist, 2000*]. This is very close to the maximum of 13m found in the simulation. While the simulation result is within the historical maximum this information certainly makes the larger wave values more questionable because they are close to the upper limit.

The waves arrived between 4.5min to 6min after the earthquake. According to the time step maps, the wave did not appear instantly after the slide. The removal of the mass depressed the water above it (Figure 8a). The crest of the wave does not appear until the depression rebounds, which happens about a minute after the slide (Figure 8b). The distance the crest travelled and the time it took were used to find average speed (Table 4). The speeds ranged

Table 4.

| Location | Distance (km) | Time Travelled (s) | Speed (km/hour) |
|---------------|---------------|--------------------|-----------------|
| Borinquen | 22.4504 | 231 | 350 |
| Aguadilla | 23.8344 | 263 | 326 |
| Punta Higuero | 17.6384 | 252 | 251 |

Distances travelled, time from crest generation to arrival, and determined speed of the wave for each of the three locations.

from 250 to 350 kilometers per hour. Tsunami speed is determined by the water depth. [NOAA, 2007] In deep water waves can travel over 500 kilometers per hour. The area of study is near a trench but overall the path from the slide to the shoreline is not very deep. Wave speed can be found by multiplying the water depth by the acceleration due to gravity and then taking the

$$\sqrt{750m * 9.8 \frac{m}{s^2}} = 86 \frac{m}{s} * \frac{1km}{1000m} * \frac{3600sec}{1hour} = 308 \frac{km}{hour}$$

square root of that. The water depth ranges from 1500m to 0m. Because the speeds calculated were averages across the entire distance, the median of the depth range can be used to get an estimate of the accuracy of these speeds. This results in a speed of 308 kilometers per hour. This is very close to the values calculated from the simulation. In fact, the average of the simulated values is 309 kilometers per hour. This suggests that the speeds for the simulation are comparable to real-world tsunamis.

Comparison to Eyewitness Reports

Wave heights simulated at Borinquen are at the upper bound of reported values at about 6m. The historical values are well constrained because the lighthouse keeper was able to see just how high the waves were. The simulated wave height at Borinquen contains that height within one standard deviation. Aguadilla has the best agreement with historic values. The historic values were found from height of water damage in the buildings in the city so they are fairly well constrained. The simulated average is within that range and plus or minus one standard deviation is also within that range. Punta Higuero has the least agreement with reported heights. This site is the only one where reported values do not come in a range. The average height of the simulation is more than twice the reported value. This large difference combined with the fact that the values found at Punta Higuero were close to the historical high at Papua New Guinea from 1998 suggest that these values may not be valid.

Reported arrival times are much less reliable than the reported heights. They have ranges of up to three minutes. In the case of Punta Higuero it is simply more than three minutes. At Borinquen, the simulated wave arrived two minutes after it was reported to have arrived. The lighthouse keeper at Borinquen claimed that the ocean began to drawdown during the shaking. The simulation does not match this description. According to the time step graphs, the trough of the wave took more than two minutes to arrive at the lighthouse. The simulated arrival times for the other two locations were within the reported ranges. The reports gave that the wave first arrived in Borinquen then Punta Higuero and finally Aguadilla. The simulation matches this arrival pattern.

Another attribute of the wave that can be compared to the historical accounts is the polarity. This does not have any specific numbers attached to it. It is simply whether the water

rose or fell first. In all three locations it is reported that dropdown occurred first. This means that the trough of the wave arrived first and the water level dropped. According to the wave height graphs (Figure 6) all three locations had the same phenomenon occur during the simulation. It is possible for dropdown to not occur if the peak of the wave arrives at the shore first and not the trough.

Sources of Error

There are two simulated values that are not close to the reported values. These are the wave height at Punta Higuero and the arrival time at Borinquen. There are multiple ways these discrepancies could have arisen. They include errors in the reported data, error in the parameters, and error in the simulation.

Wave heights at Punta Higuero are the least constrained among the three locations. The only evidence of wave height left at the location were fish that were transported to railroad tracks that were 5.2 meters above normal sea level. This means that the wave could have been than the tracks, this is just a lower bound for the height. Other sources of error include simulation error or error in the original inputs. Near-shore bathymetry is known to cause problems with simulations. The resolution of the bathymetry grid is integral to giving accurate results. If the grid resolution is what caused the error, then it should be corrected by decreasing cell size and running the simulation again with the same inputs.

If that does not reduce the error, then it must have been caused by incorrect inputs into the model. *Hornbach et al.*, [2008] ran a secondary simulation where the volume of the slide was cut in half. This reduced the wave amplitudes by more than half. While this could make the amplitude at Punta Higuero more realistic, the other two locations' heights would most likely be

reduced, which would put them below the reported values. Besides a change to the volume parameters, a modification of the location of the slide could affect the impact of the wave.

CONCLUSIONS

A submarine slide is a plausible mechanism for the generation of the 1918 Puerto Rico tsunami. The wave created in the simulation matched reported wave heights. GEOWAVE was able to make a realistic submarine slide driven tsunami based both on wave heights and wave speeds. In some spots the wave height became a high but in those areas there was not a good constraint on the actual wave so it is unknown just how much higher the simulated wave was.

This particular submarine slide is less likely to be the source of the tsunami. The arrival times of the wave for the simulation were all close to the maximum reported time. In the case of Borinquen, the simulated time was well over the reported time. The reports from Borinquen indicate that the initial drawdown occurred during the earthquake. This would mean that the slide that caused this wave would have had to have been closer to Borinquen than the one modeled. The strongest evidence for this particular headscarp and associated slide were the buried cables. There could have been multiple slides during the event, one that made the tsunami and another that buried the cables.

RECOMMENDATIONS FOR FUTURE WORK

Future research in this area would include other possible sources for the tsunami. Modeling the earthquake and different slides could improve agreement with reported values. It is possible to simulate more than one tsunami source at a time in GEOWAVE. It would be interesting to see how multiple waves interact with each other.

Further constraining the reported values would also be beneficial to the study. Taking cores in Puerto Rico could reveal just how high the wave was and how far inland the water came. This would make it easier to throw out sources that do not work.

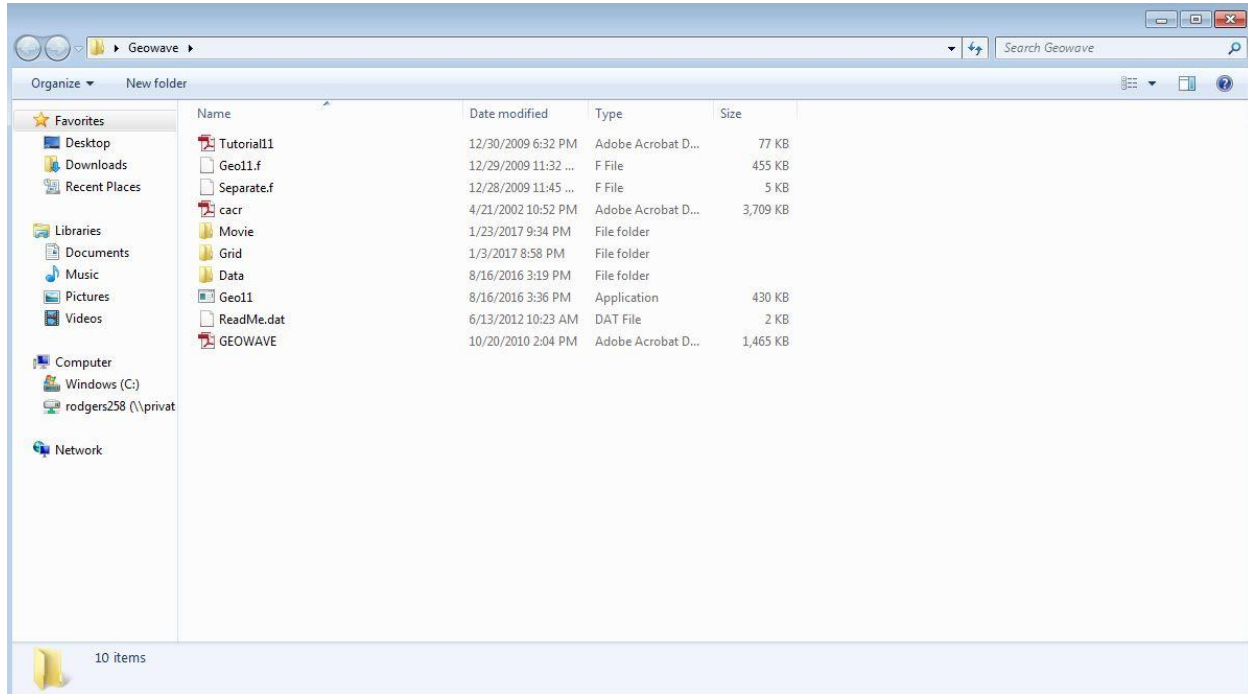
REFERENCES CITED

- Applied Fluids Engineering Inc., Center for Applied Coastal Research (2008) Geowave 11 tutorial. University of Delaware, Newark
- Briggs, R. P., & Gordon, W. A. (1961). Geology of Kewanee interamerican oil company test well number 4CPR, northern Puerto Rico. Puerto Rico Mining Commission.
- Geist, E. L. (2000). Origin of the 17 July 1998 Papua New Guinea tsunami: earthquake or landslide. *Seismological Research Letters*, 71(3), 344-351.
- Hornbach, M. J., Frohlich, C., Mann, P., Mondziel, S. A., & Grindlay, N. R. (2008). Did a submarine slide trigger the 1918 Puerto Rico tsunami?. *Science of Tsunami Hazards*, 27, 2, 22-31.
- Jansma, P. E., Mattioli, G. S., & Lopez, A. (2000). Neotectonics of Puerto Rico and the Virgin Islands northeastern Caribbean from GPS geodesy. *Tectonics*, 19(6), 1021-1037
- Krause, D. C., White, W. C., Piper, D. J. W., & Heezen, B. C. (January 01, 1970). Turbidity Currents and Cable Breaks in the Western New Britain Trench. *Geological Society of America Bulletin*, 81(7), 2153-2160.
- Lopez-Venegas, A. M., ten Brink, U. S., & Geist, E. L. (2008). Submarine landslide as the source for the October 11, 1918 Mona Passage tsunami: Observations and modeling. *Marine Geology*, 254(1), 35-46.
- Mader, C. L., & Gittings, M. L. (2002). Modeling the 1958 Lituya Bay mega-tsunami, II. *Science of Tsunami Hazards*, 20(5), 241-250.
- Mercado, A., & McCann, W. (1998). Numerical simulation of the 1918 Puerto Rico tsunami. *Natural Hazards*, 18(1), 57-76.
- Mondziel, S., Grindlay, N., Mann, P., Escalona, A., & Abrams, L. (2010). Morphology, structure, and tectonic evolution of the Mona canyon (northern Mona passage) from multibeam bathymetry, side-scan sonar, and seismic reflection profiles. *Tectonics*, 29, 2.
- NOAA (National Oceanic and Atmospheric Administration). (February 22 2017). Retrieved February 22, 2017, from <http://www.tsunami.gov/?page=tsunamiFAQ>
- Reid, H. F., and S. Taber (1919), The Porto Rico earthquakes of October-November 1918, *Bull. Seismol. Soc. Amer.*, 9(4), 94-127.
- Tappin, D. R., Watts, P., & Grilli, S. T. (2008). The Papua New Guinea tsunami of 17 July 1998: anatomy of a catastrophic event. *Natural Hazards and Earth System Science*, 8(2), 243-266.
- Taylor, L.A., Eakins, B.W., Carignan, K.S., Warnken, R.R., Sazonova, T., Schoolcraft, 2008. Digital Elevation Models of Puerto Rico: Procedures, Data Sources and Analysis, NOAA Technical Memorandum NESDIS NGDC-13, National Geophysical Data Center, Boulder, CO, 27 pp.
- Watts, P., Grilli, S. T., Kirby, J. T., Fryer, G. J., & Tappin, D. R. (2003). Landslide tsunami case studies using a Boussinesq model and a fully nonlinear tsunami generation model. *Natural Hazards And Earth System Science*, 3(5), 391-402.

APPENDIX

Step by Step Instructions

1. Download GEOWAVE from http://www1.udel.edu/kirby/programs/funwave/funwave_download.shtml
2. Extract the contents of the file to a folder on your computer.
3. Within that same folder create three folders called Movie, Grid, and Data. These are the folders where some of the output files will be sent.



4. Determine the units for the horizontal and vertical data in your bathymetry data

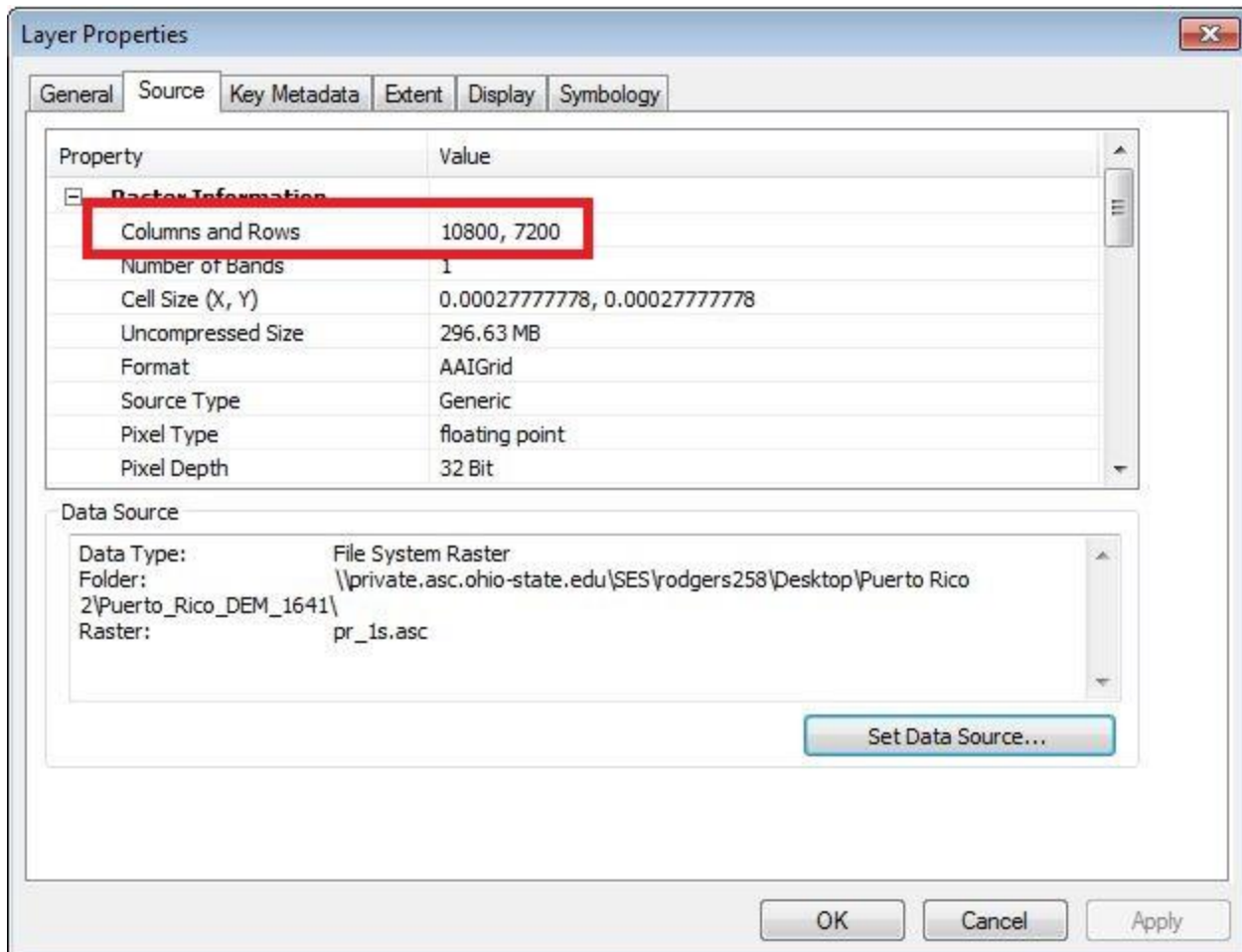
DEM perspective image.

| | |
|--------------------------------|--|
| <i>Name</i> | Puerto Rico |
| <i>States</i> | Puerto Rico |
| <i>Region</i> | Caribbean |
| <i>Extent</i> |  |
| <i>Date Completed</i> | 2007-06-22 |
| <i>Type</i> | Coastal Inundation |
| <i>Horizontal Datum</i> | WGS 84 |
| <i>Projection</i> | Geographic (degrees) |
| <i>Vertical Datum</i> | MHW (meters) |
| <i>Vertical Transformation</i> | Source elevation data transformed vertically using constant offset. |
| <i>Coverage</i> | Bathy-topo |
| <i>Cell Size</i> | 1 arc-second |
| <i>Registration</i> | Grid-node |
| <i>Version</i> | 2 |
| <i>Source</i> | NOAA / NGDC / MGG |
| <i>Developer</i> | NOAA / NGDC / MGG |
| <i>Project</i> | NOAA Tsunami Inundation |
| <i>Contact</i> | Barry W Eakins @ NOAA / NGDC |

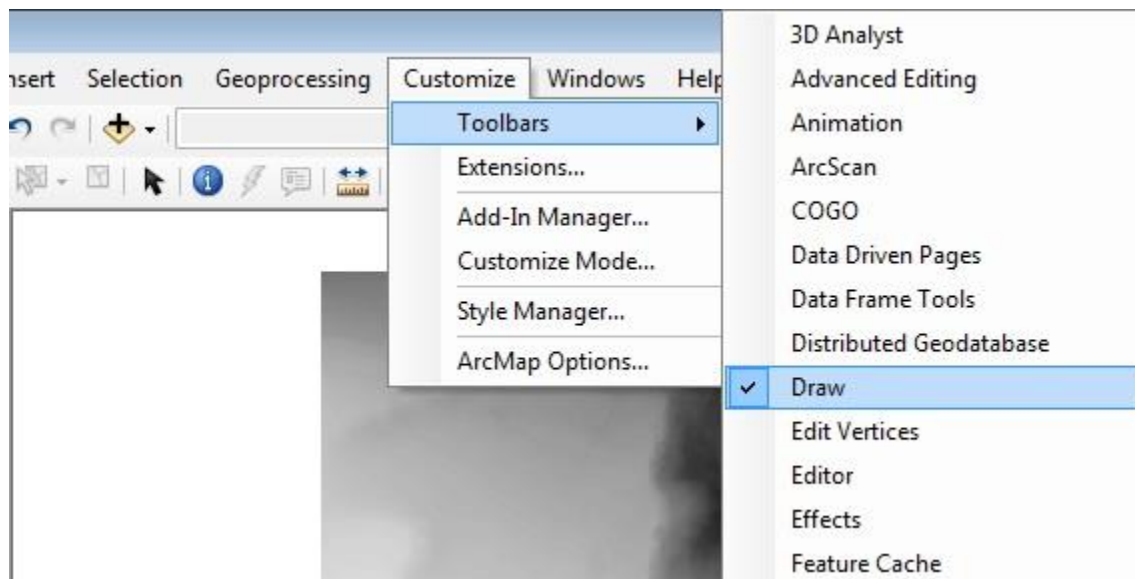
5. To find the horizontal units you can just load the map into ArcGIS by dragging it in, hover your mouse over the map, and look in the lower right.



6. So this example is meters for the vertical units and decimal degrees for the horizontal. GEOWAVE will ask you for this later.
7. If you have not already, load the data into ArcGIS.
8. By default, GEOWAVE is limited to an 800 by 800 ascii grid as an input. Most bathymetric data will be larger than this.
9. To check what size yours is, find the file in the table of contents to the left and double click its name.
10. Under the source tab there will be a row called “Columns and Rows” if these numbers are above 800 then the grid must be decreased in size.



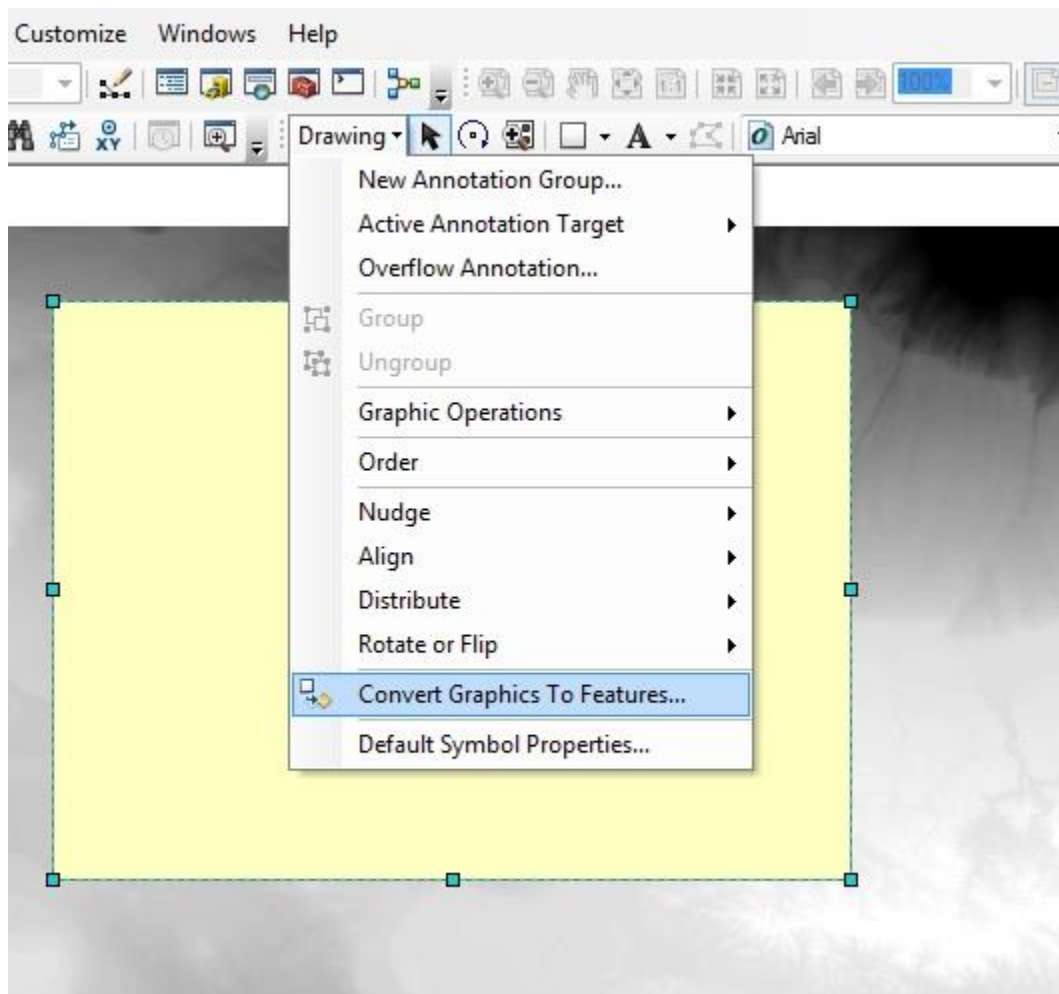
11. A good way to cut the number of cells is to focus on a smaller area.
12. The easiest way to do this is to draw a rectangle over the area you are interested in.
13. Go to the Customize menu, Toolbars, and make sure Draw is checked.



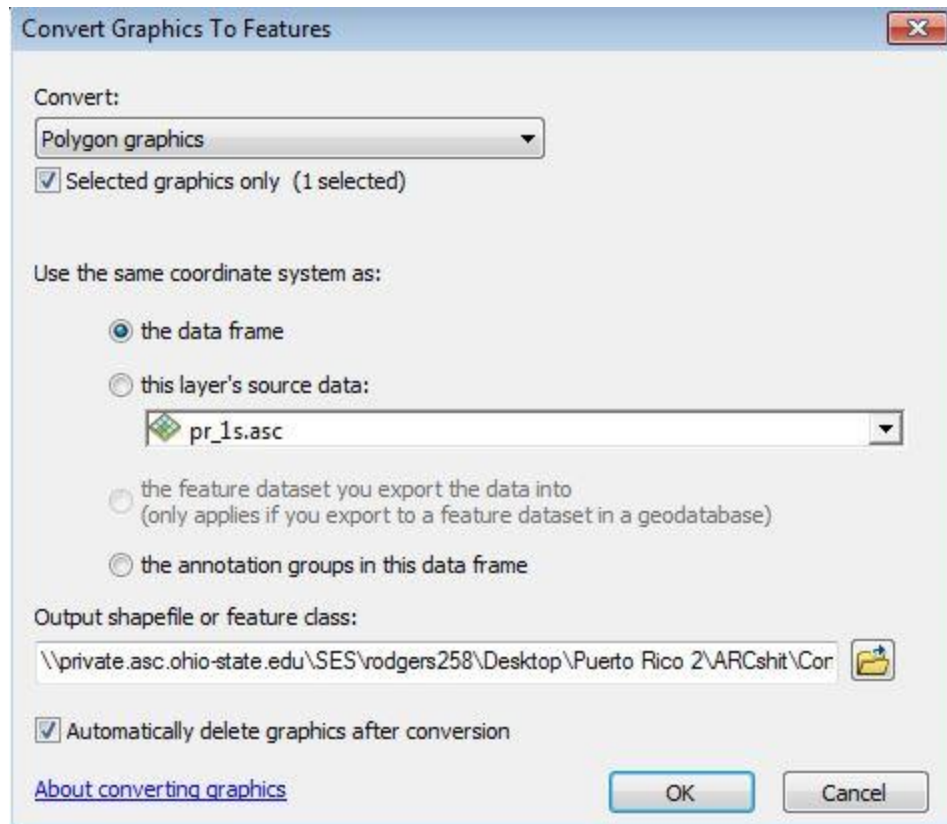
14. If the rectangle shape is not selected in the Draw Shape button hit the down arrow next to it and select Rectangle. Then click the shape.



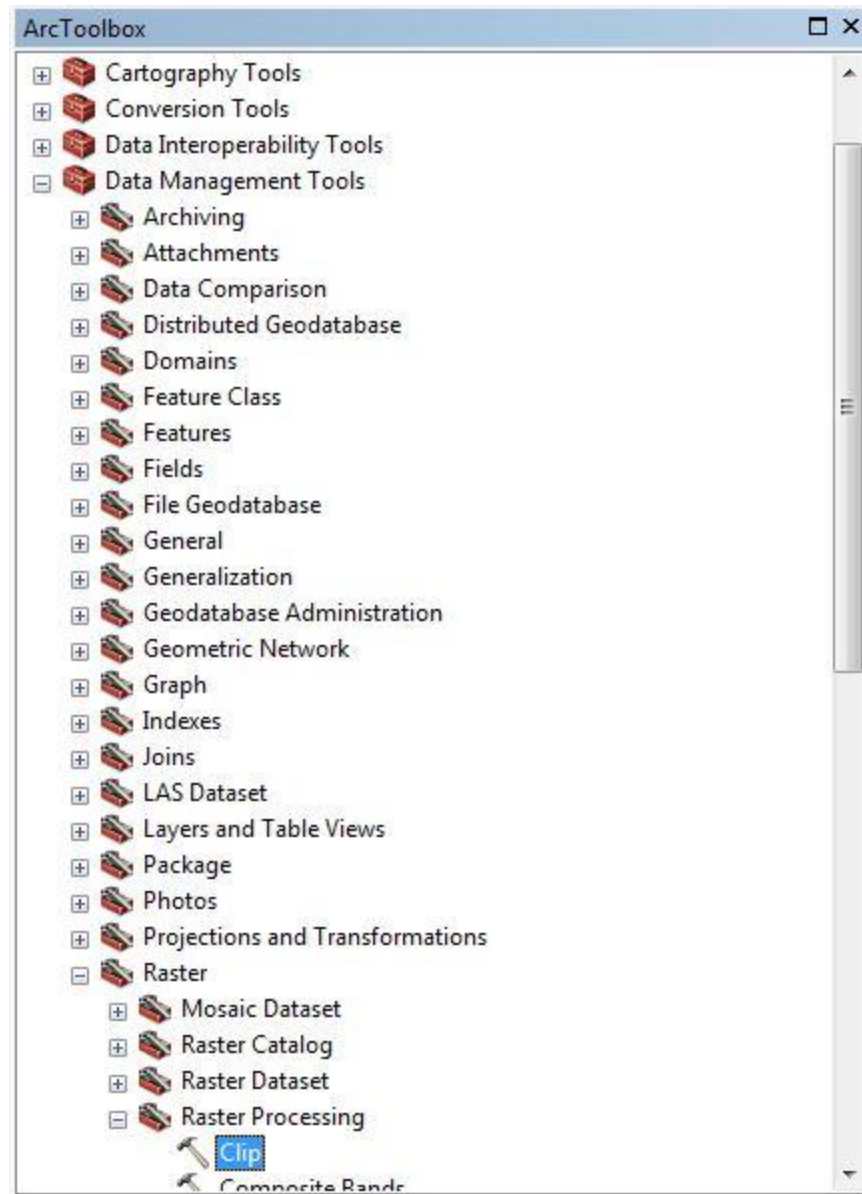
15. Click and drag to draw a rectangle over the area you would like to investigate.
16. Now click the Drawing drop down menu in the Draw toolbar and select “Convert Graphics to Features.”



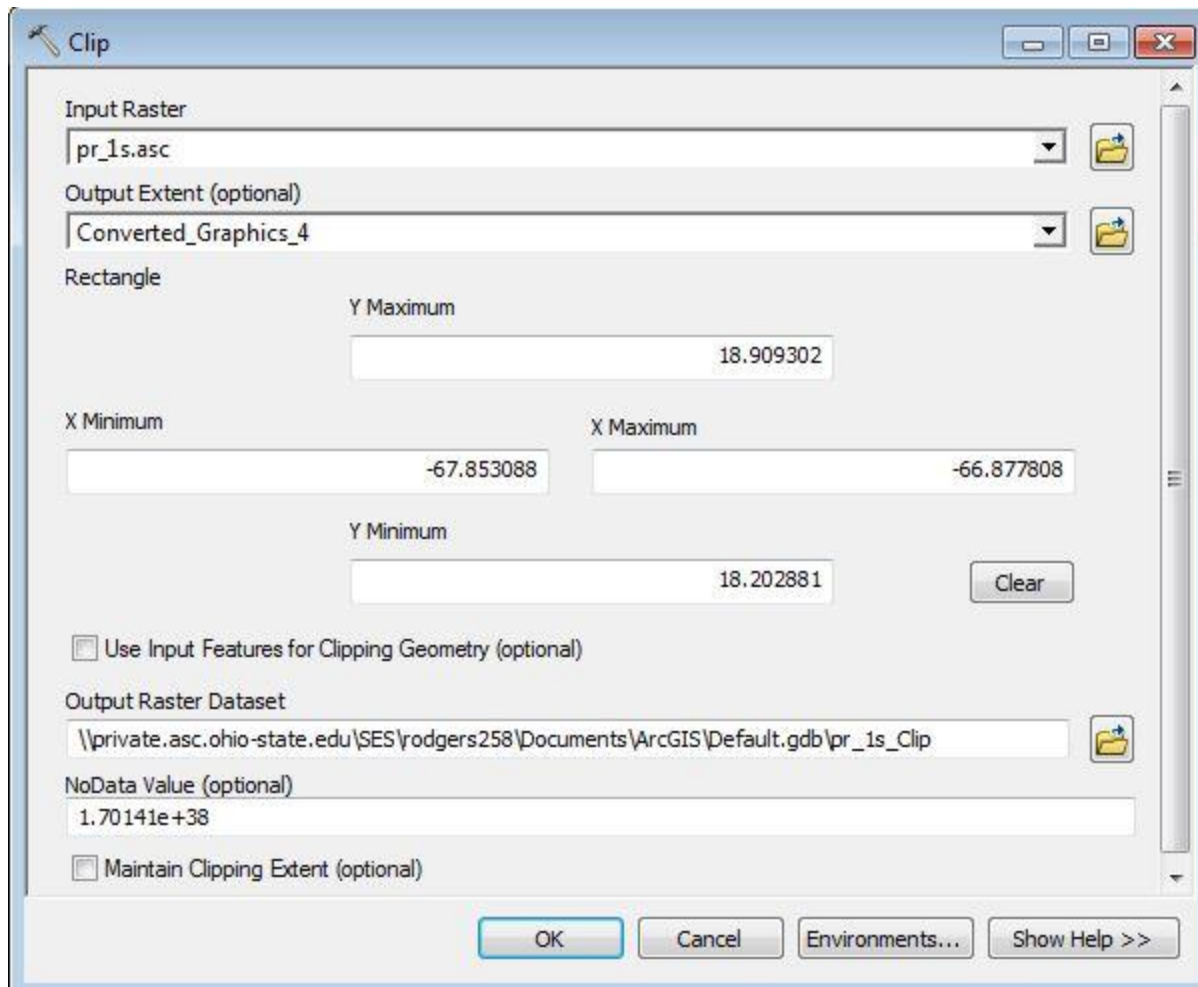
17. The default options should be fine but make sure “Automatically delete graphics after conversion” is checked.



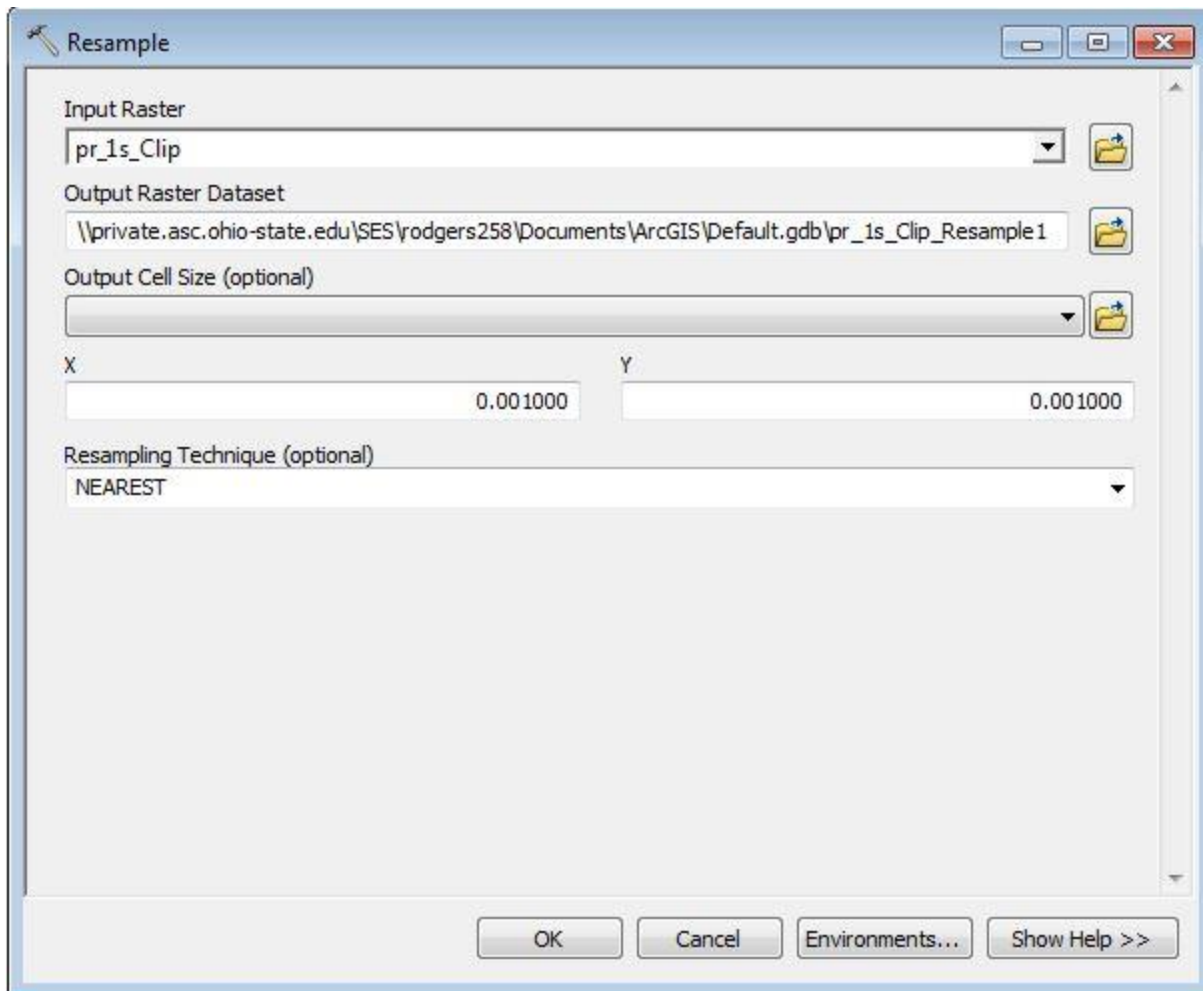
18. Click yes, you would like to add the exported data as a layer.
19. Now go to the Geoprocessing menu and select ArcToolbox.
20. Expand “Data Management Tools,” “Raster,” and “Raster Processing” and then double click on “Clip.”



21. Select your bathymetry file for the input and the converted graphic file for your output.
(If you knew the coordinates of the rectangle you wanted you could enter those without creating the graphic.)
22. Enter 1.70141e+38 as the NoData Value.

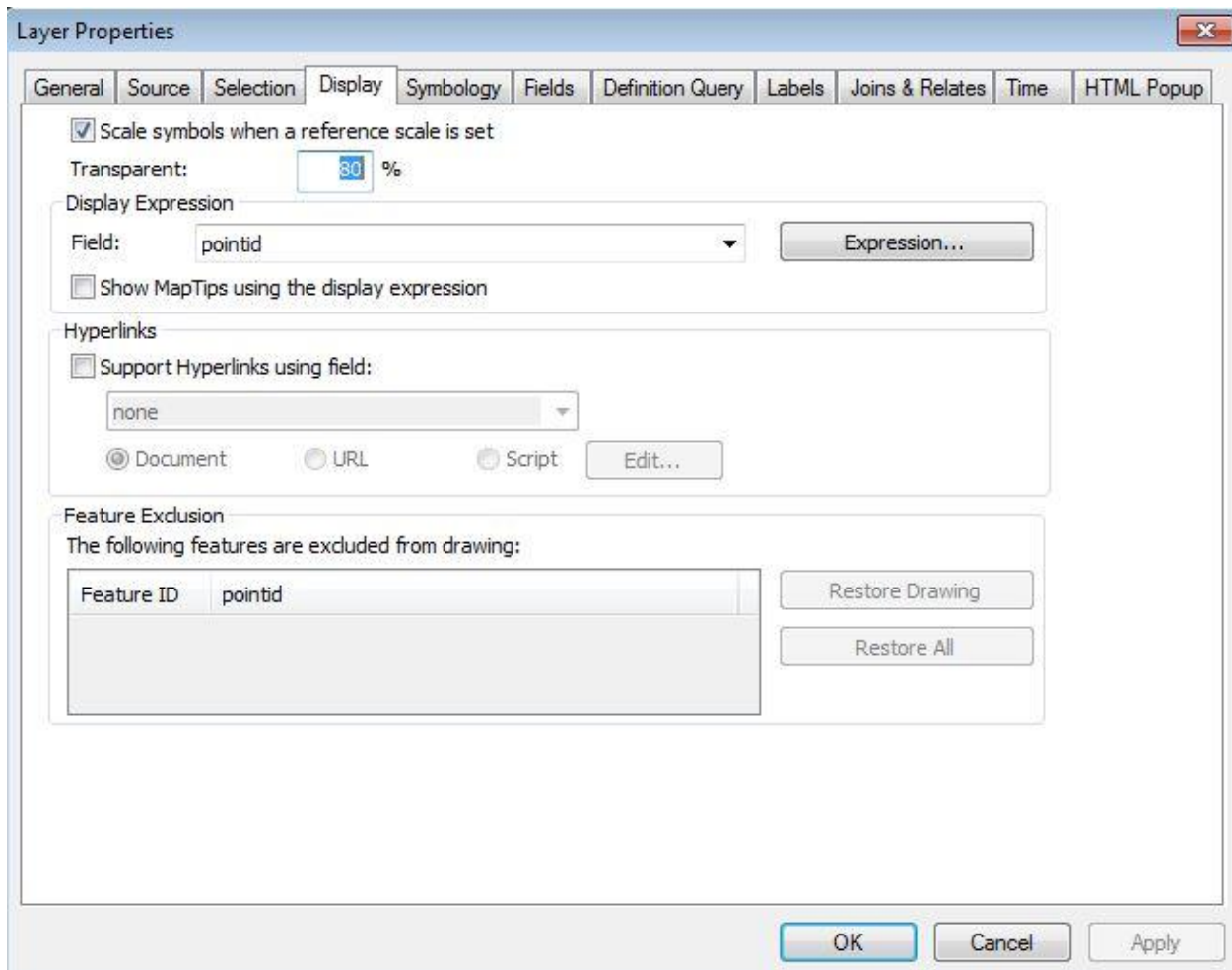


23. It can take a while to complete the clip but it will automatically add the new bathymetry map when it is done. Be sure to uncheck the larger map and the converted graphic in the table of contents to see it.
24. Now double click on its name to check the grid size again. If it is still not less than 800 by 800 columns and rows, we can increase the cell size.
25. Go to the Geoprocessing menu and select ArcToolbox.
26. Expand "Data Management Tools," "Raster," and "Raster Processing" and then double click on "Resample."
27. Select the clipped bathymetry map for the input.
28. Edit the X and Y values for cell size and make them larger than what is listed by default. Make sure to keep them equal to each other to maintain square cells.

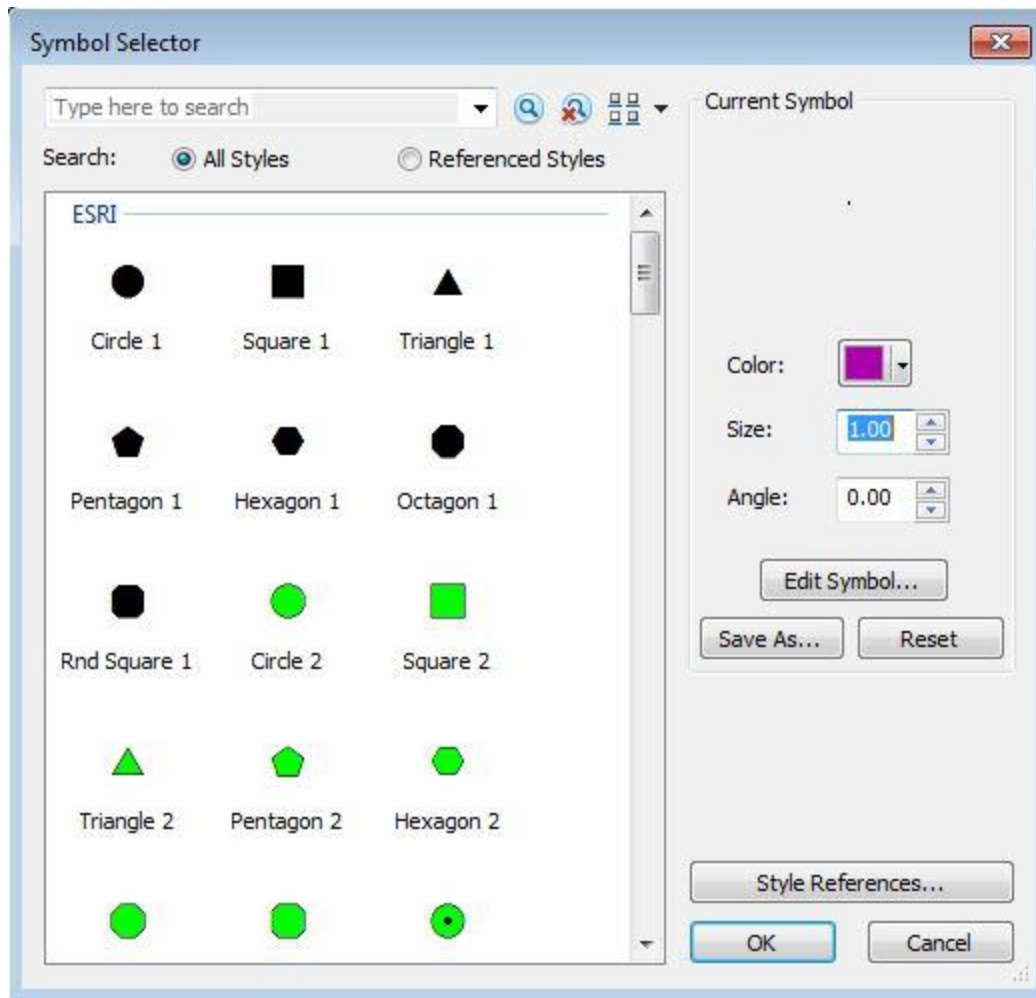


29. The other default options are fine.
30. Click OK
31. Again it can take a while to process but will automatically add the map when finished.
32. Double click its name in the table of contents to check its size.
33. If it is not below 800 by 800 then you will have to resample again.
34. If it is far below 800 by 800 you may want to resample again for a higher resolution as it will make the GEOWAVE simulation more accurate.
35. To recreate the original seafloor, you have to change the bathymetry map to a point grid. This can be done through the Geoprocessing menu and ArcToolbox.
36. Expand "Conversion Tools," and "From Raster," and then double click on "Raster to Point."
37. Select your final bathymetry grid as the input and hit OK.
38. This will give you selectable, editable points over your bathymetry grid.

39. It can be hard to see the detail of the bathymetry grid through these points but you can double click on the name of the layer and go to the Display tab and adjust the transparency field.



40. You can also go to the Symbology tab and hit the symbol to bring up the menu to change its size to make them smaller.

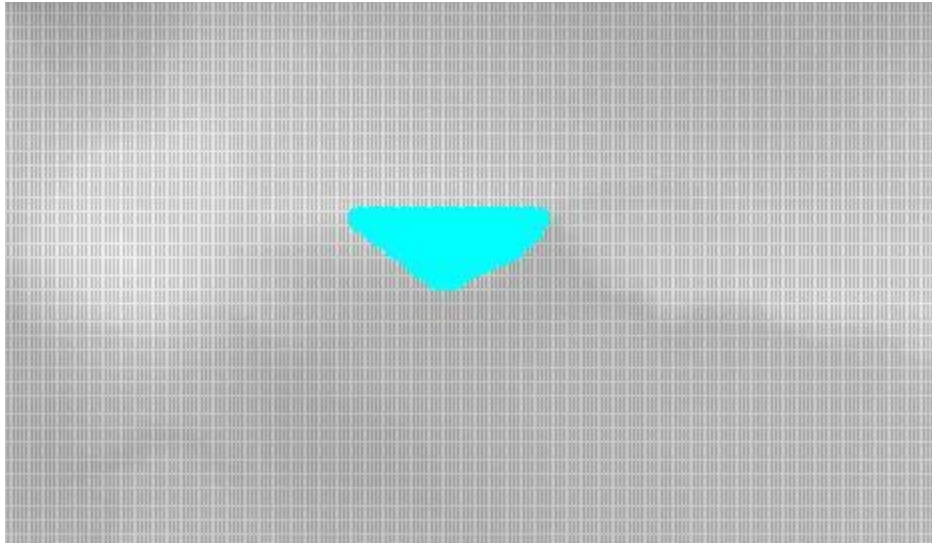


41. Now you need to select the points that make up what you believe to be the missing seafloor.
42. Select the dropdown menu next to the Select Features button and choose Select by Polygon.



43. Go to the grid and click out the boarder of the missing seafloor double clicking to finish.

44. Make sure you have the correct points selected.



45. Right click on the point layer and choose Open Attribute Table.

46. Change the listed values to only the selected points.

Table

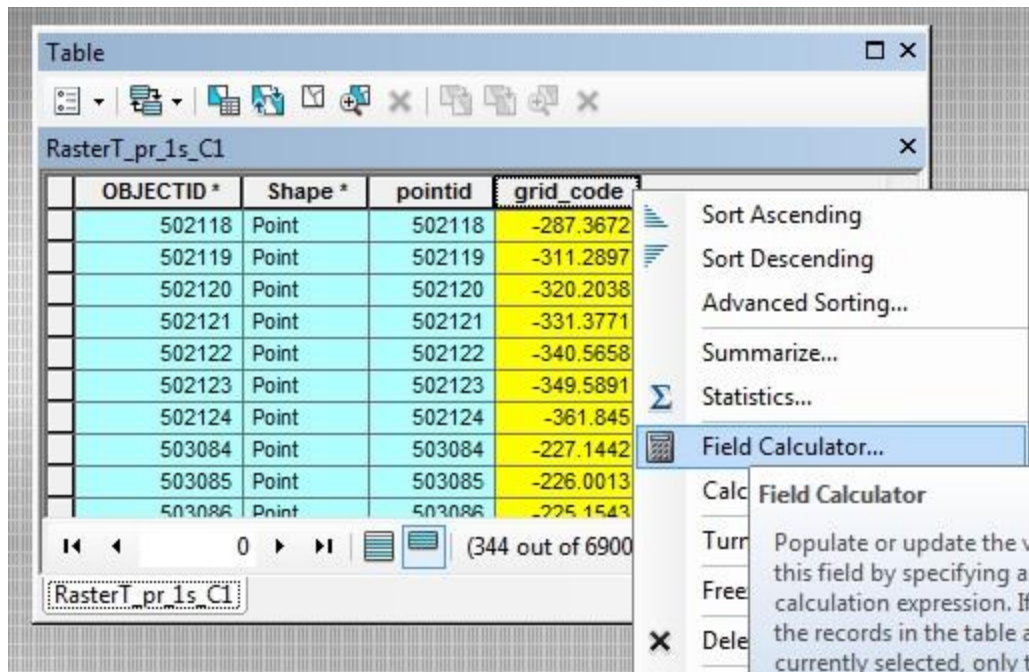
RasterT_pr_1s_C1

| | OBJECTID * | Shape * | pointid | grid_code |
|--|------------|---------|---------|-----------|
| | 502118 | Point | 502118 | -287.3672 |
| | 502119 | Point | 502119 | -311.2897 |
| | 502120 | Point | 502120 | -320.2038 |
| | 502121 | Point | 502121 | -331.3771 |
| | 502122 | Point | 502122 | -340.5658 |
| | 502123 | Point | 502123 | -349.5891 |
| | 502124 | Point | 502124 | -361.845 |
| | 503084 | Point | 503084 | -227.1442 |
| | 503085 | Point | 503085 | -226.0013 |
| | 503086 | Point | 503086 | -225.1543 |

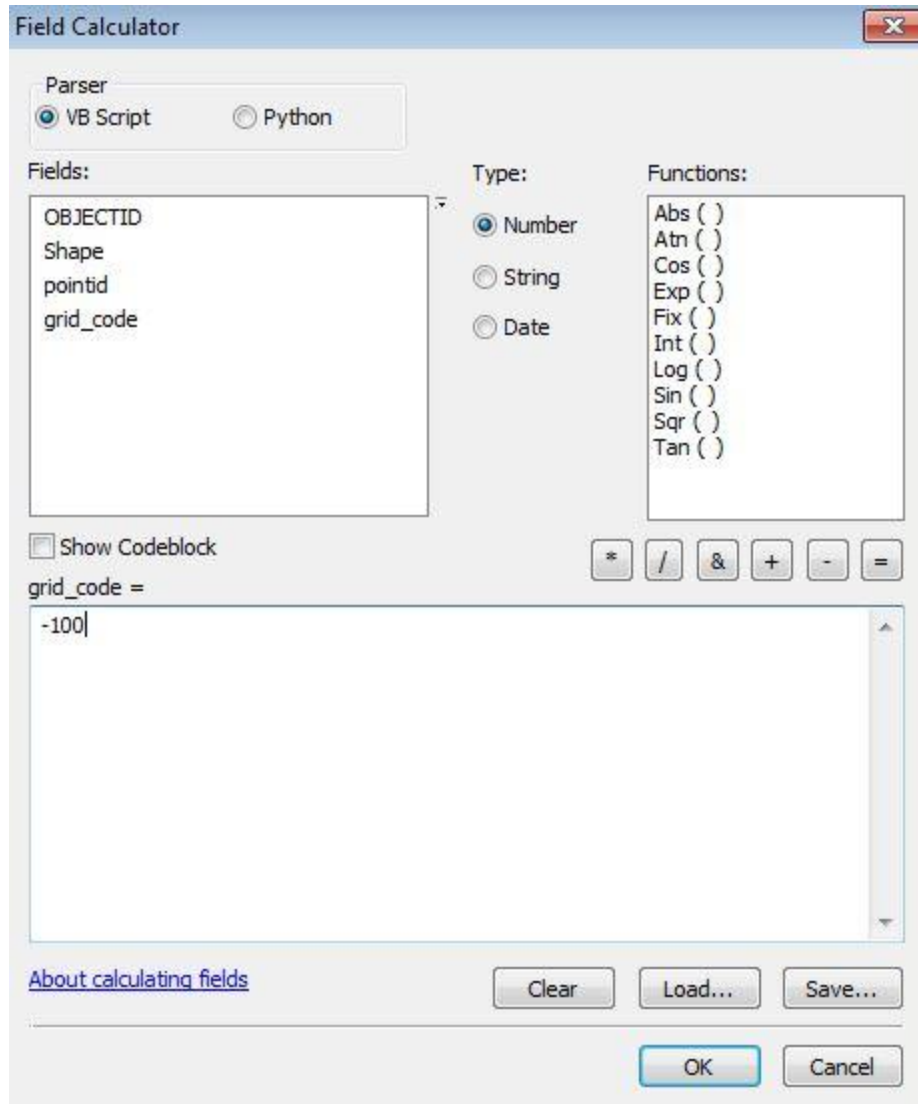
0 (344 out of 690032 Selected)

RasterT_pr_1s_C1

47. Right click on the grid_code column heading and choose Field Calculator.

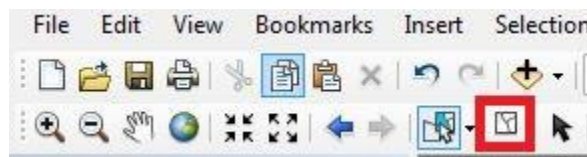


48. Determine the original height of the seafloor and enter that in the “grid_code =” box and click OK.



49. Now you have to turn the point grid back into a raster grid.

50. First unselect the points you edited.



51. Next click on the Geoprocessing menu and then ArcToolbox.

52. Expand “Conversion Tools,” and “To Raster,” and then double click on “Point to Raster.”

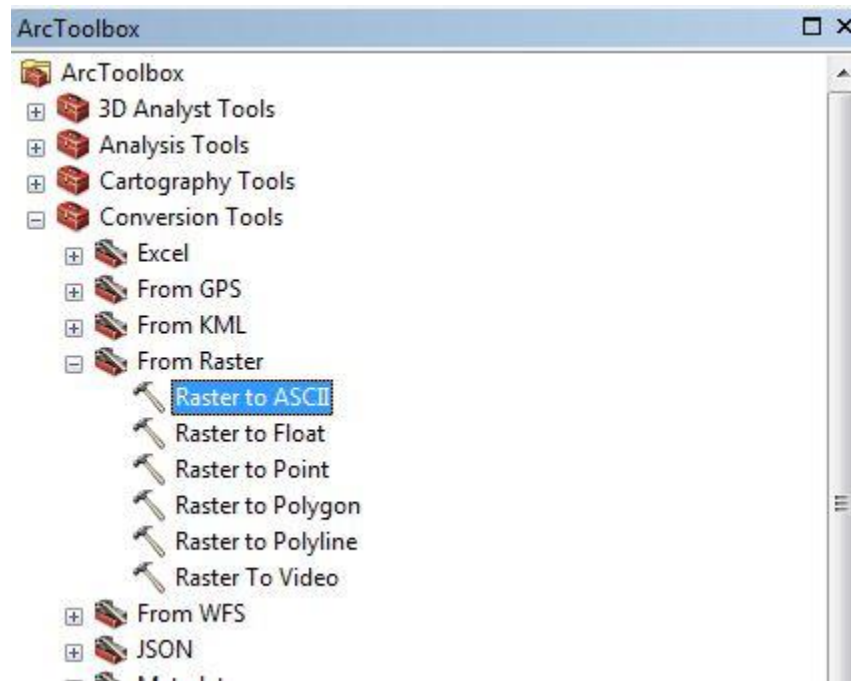
53. Enter the point grid for the input features.

54. Change the Value Field to grid_code.

55. Change the cell size to the size you chose from step 28.

56. Click OK.

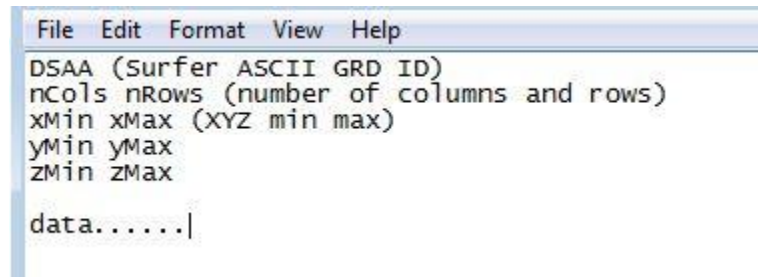
57. This can take a while to process but it will automatically be added when finished.
58. You should now have a bathymetry map that shows the missing seafloor added back.
59. Now it is time to create the ascii grid.
60. Go to the Geoprocessing menu and select ArcToolbox.
61. Expand “Conversion Tools,” and “From Raster,” and then double click on “Raster to ASCII.”



62. Select your bathymetry map that is less than 800 by 800 as the input.
63. Change the output location to a place you can easily access.
64. Hit OK.
65. GEOWAVE only takes the Surfer format of ascii grids, not the ESRI form which is what you created.
66. If you have access to Surfer, you can load this ascii grid into Surfer to convert it.
67. If you do not have Surfer, you will have to manually convert it.
68. Open the ascii file that you just created with Notepad.
69. At the top you will see a header with information about the grid. This is what needs to be changed to Surfer format to work with GEOWAVE.

| File | Edit | Format | View | Help |
|--------------|------|--------|--------------|------|
| ncols | | | 777 | |
| nrows | | | 786 | |
| xllcorner | | | -67.99736111 | |
| yllcorner | | | 17.74170557 | |
| cellsize | | | 0.0016 | |
| NODATA_value | | | -9999 | |

70. The new header needs to have this information:

A screenshot of a text editor window with a menu bar (File, Edit, Format, View, Help) and a text area containing a header template for a Surfer ASCII GRD file. The text is as follows:

```
DSAA (Surfer ASCII GRD ID)
nCols nRows (number of columns and rows)
xmin xmax (XYZ min max)
ymin ymax
zmin zmax
data.....|
```

71. Copy your original header and put it into a separate file. You will need it later.

72. Enter DSAA as the top line of the new header.

73. Enter the number of columns and rows in the second line separated by a space. You can find these from double clicking the name of the bathymetry map in the ArcGIS table of contents.

74. xMin and yMin are equal to xllcorner and yllcorner from the original header respectively.

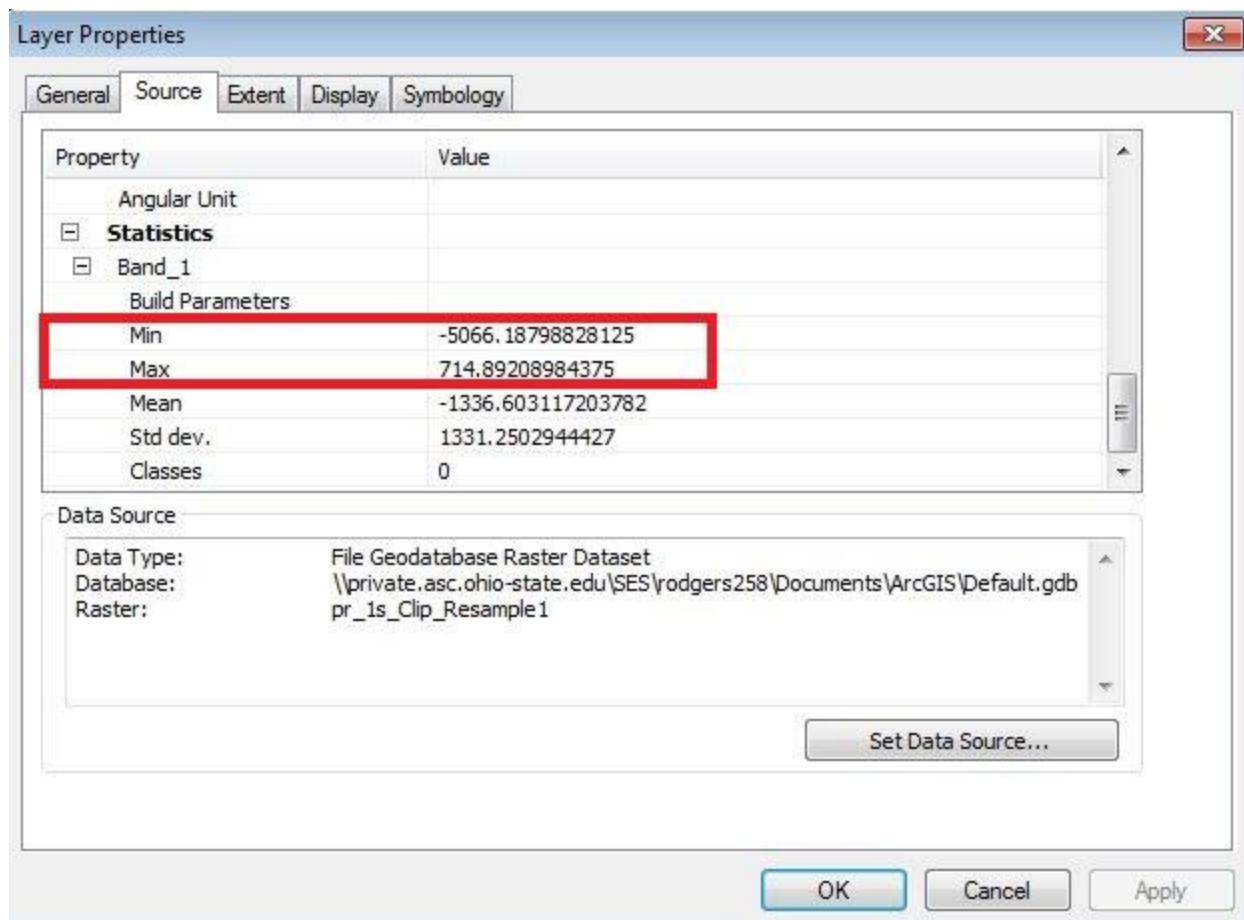
75. To find xMax and yMax use the following equations.

76. $xMax = xMin + (0.5 * cellsize) + (cellsize * (ncols - 1))$

77. $yMax = yMin + (0.5 * cellsize) + (cellsize * (nrows - 1))$

78. Enter those values after the xMin and yMin values separated by a space.

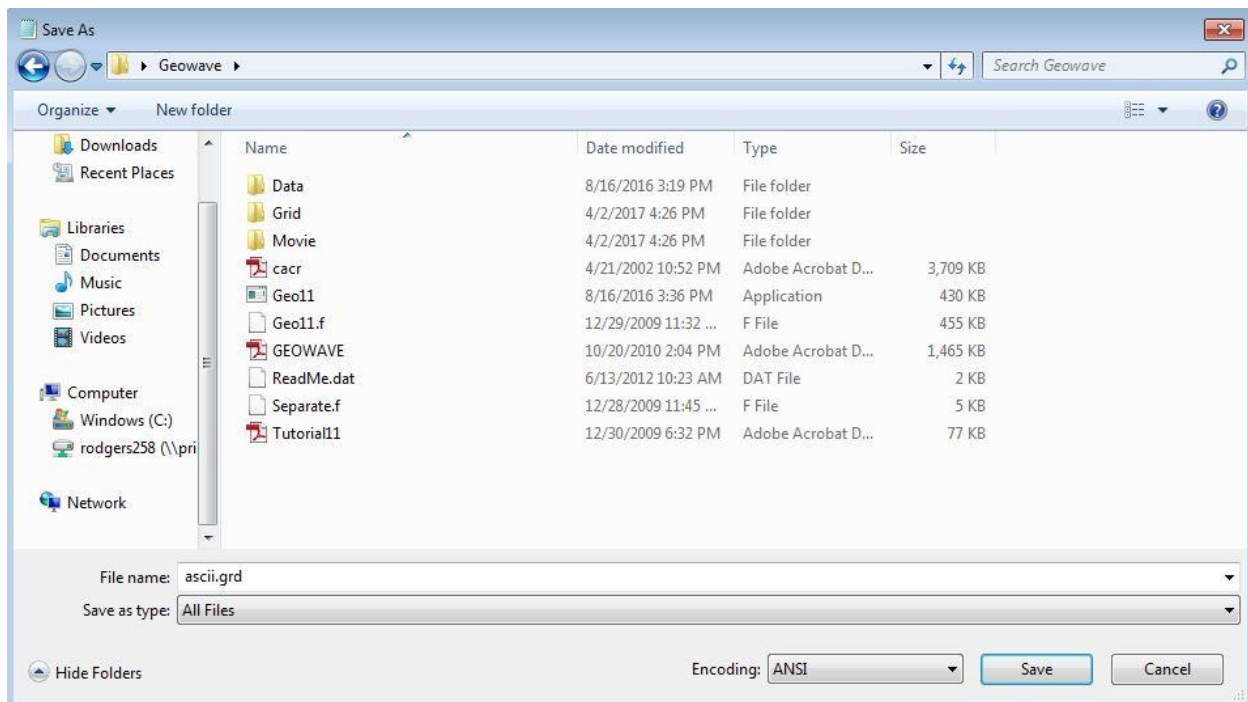
79. The zMin and zMax values can be found in ArcGIS in the same table that the number of columns and rows were found.



80. Copy and paste those values into the next row in the header separated by a space.

```
File Edit Format View Help
DSAA
777 786
-67.99656111 -66.75416111
17.74250557 18.99930557
-5977.0439453125 1158.04296875
```

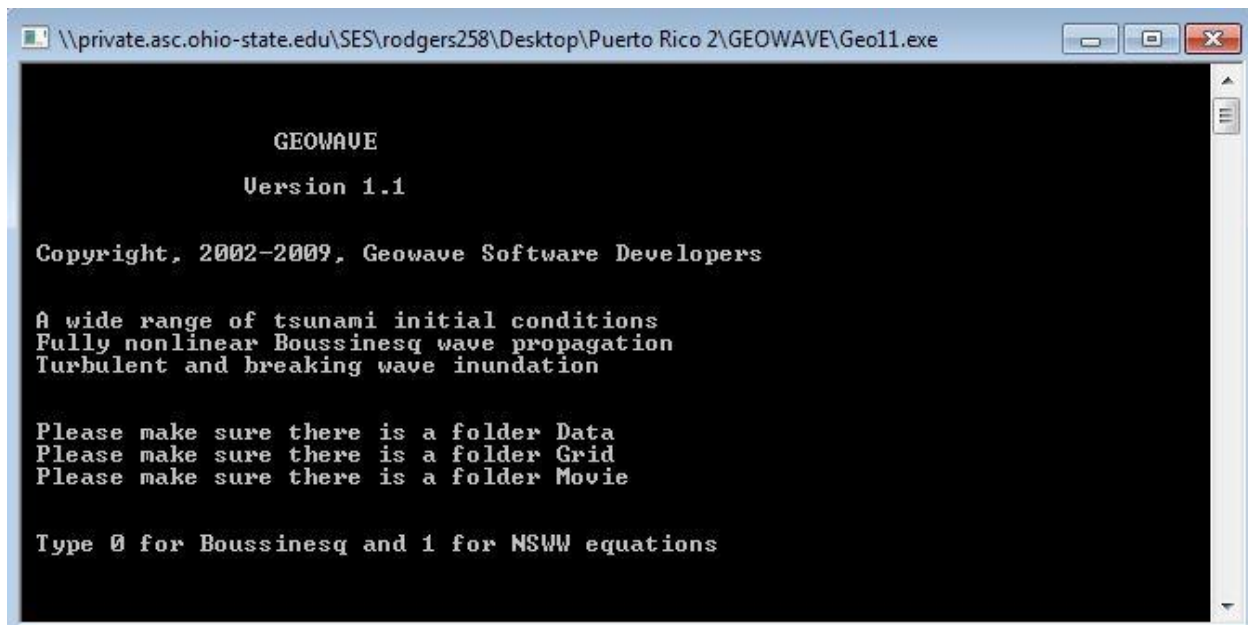
81. Click file, Save As on the ascii file



82. Change the file type from .txt to All Files and name the file with a .grd ending (ascii.grd)

83. Save it in the same folder where the GEOWAVE program is located.

84. Now open GEOWAVE



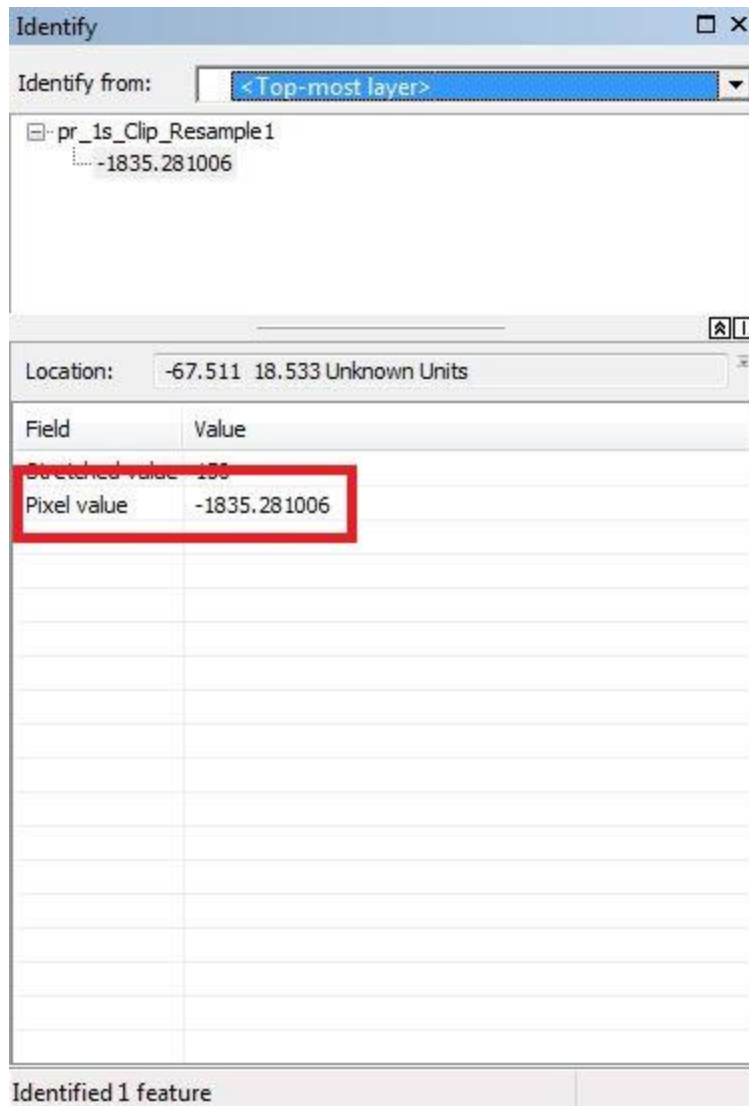
85. Enter 0 for Boussinesq and hit enter.

86. Enter the name of the ascii file you just saved (ascii.grd)

87. Enter 0 to confirm it is a Surfer ascii grid and hit enter.

88. Enter 0 to output Surfer ascii grids and hit enter.

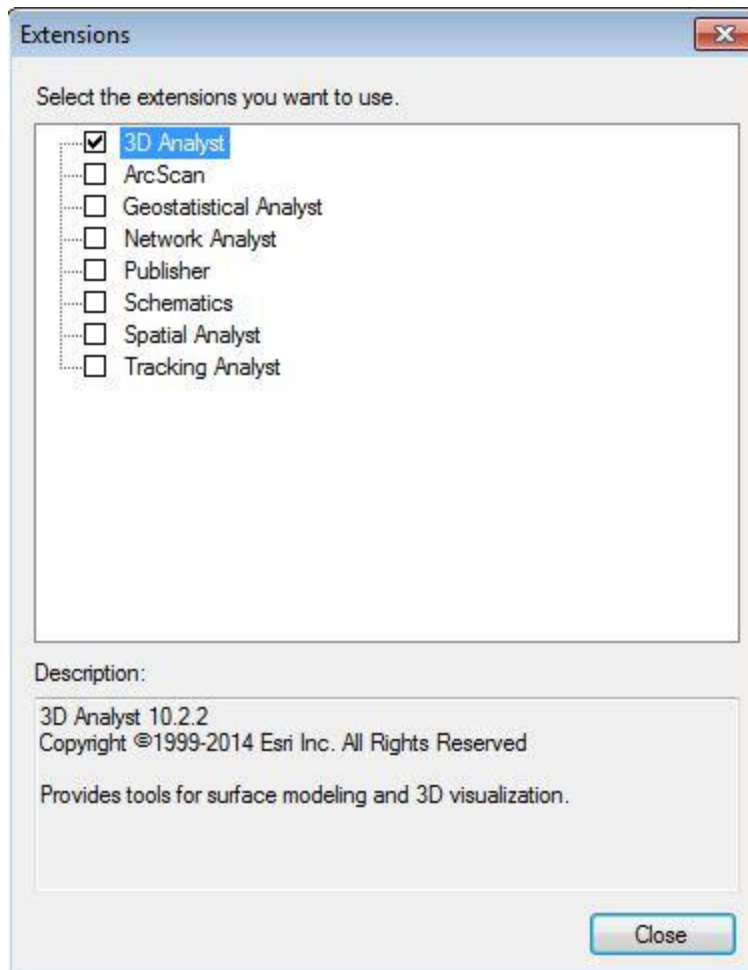
89. GEOWAVE will now open your ascii file. If you did not convert the header correctly, save it as a .grd, or entered the name wrong GEOWAVE will close. If you did all of that correctly it will move on to the next step.
90. Select whether your depth values are listed as positive or negative in the bathymetry data. This will change depending on the source of the data.
91. Enter the horizontal units of the grid found in step 5.
92. Enter the vertical units from step 4.
93. Enter 1 to not smooth bathymetry, that was already done when decreasing the number of cells.
94. Enter 0 for the number of wave gauges.
95. Enter 0 for the number of Lagrangian markers.
96. Enter the number of tsunami sources. This study only used one.
97. Enter the type of source. This study used (1) translational slide.
98. Enter the time for the tsunami to be created. This can be put as 0 to start tsunami creation as soon as the simulation starts. This is more useful if there are multiple sources.
99. Using ArcGIS find the X and Y coordinates of the center of the slide. Enter the X coordinate.
100. Enter the Y coordinate.
101. If North was up on your original bathymetry map enter 0 for the next input.
102. Enter the angle that the slide traveled counterclockwise from North. (Due West would be 90, due East would be 270).
103. In ArcGIS, right click on the center of the slide and hit Identify. The Pixel Value is the depth at that location in meters. Enter that number into GEOWAVE and hit enter.



104. If the slope of the seafloor in the area is known, enter that value. If it is not known, it can be found in ArcGIS.

105. First go to the Customize menu and click Extensions.

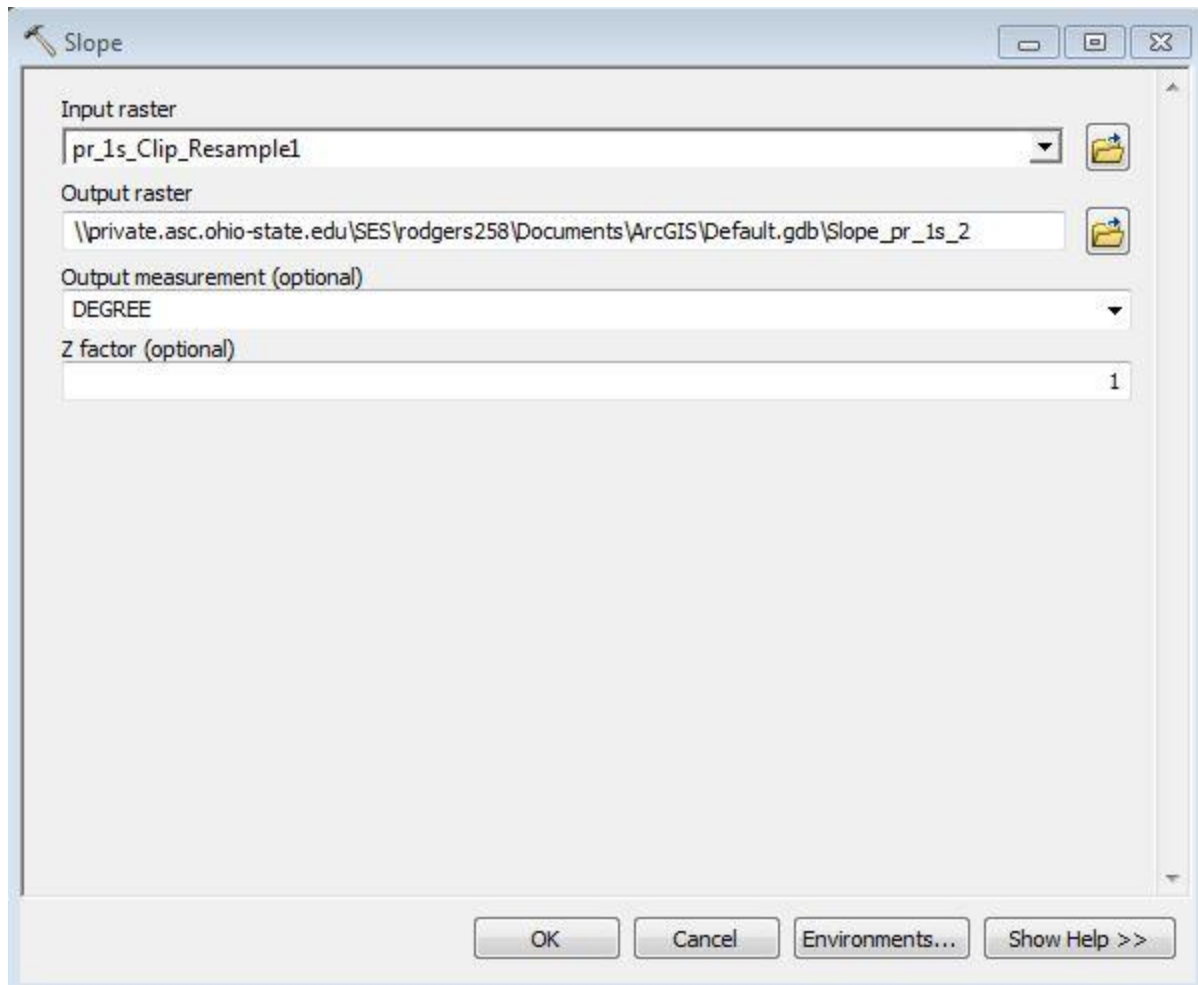
106. Make sure 3D Analyst is checked.



107. Now go to Geoprocessing and select ArcToolbox.

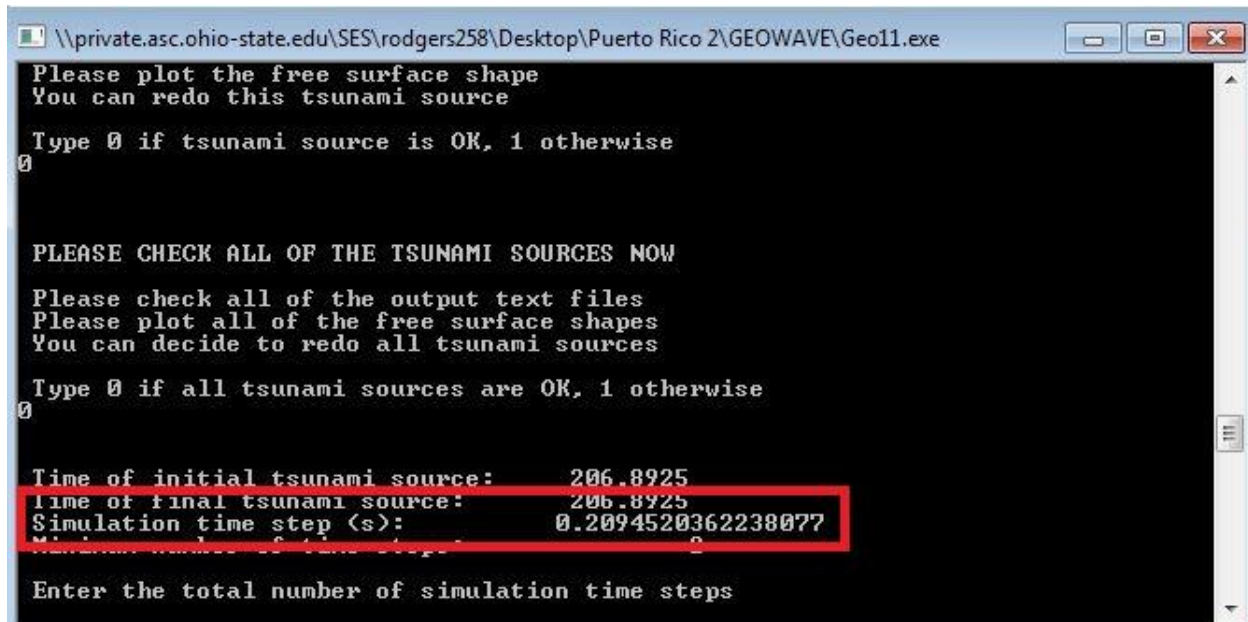
108. Expand “3D Analyst Tools” and “Raster Surface.” Double click on Slope.

109. Select your bathymetry map as the input and click OK.



110. The slope map will automatically be added when it is created. Find the area of the slide, right click, and select identify. The Pixel Value is the slope at that point.
111. Enter this value for in GEOWAVE and hit enter.
112. The slide length is defined as the length of the body parallel to the direction of movement. Enter your value and hit enter.
113. The slide thickness is defined as the vertical extent of the slide. Enter your value and hit enter.
114. Slide width is defined as the length of the slide perpendicular to the slide direction. Enter your value and hit enter.
115. The maximum tsunami cutoff width is the width of the wave that the model will simulate. If you enter 100 here the simulation will look like the wave is in a channel 100m wide. To get the full scope of the wave, enter a large value (100000m).
116. Enter the slide bulk density and hit enter.
117. Enter 0 that the tsunami source is OK. (If you enter 1 looking to change your values GEOWAVE will just close).
118. Enter 0 again to confirm all sources are OK.

119. Now you define the length of the simulation. GEOWAVE defines a “real world” time for every step of the simulation.



The screenshot shows a command window titled "\\private.asc.ohio-state.edu\\SES\\rodgers258\\Desktop\\Puerto Rico 2\\GEOWAVE\\Geo11.exe". The window contains the following text:

```
Please plot the free surface shape
You can redo this tsunami source

Type 0 if tsunami source is OK, 1 otherwise
0

PLEASE CHECK ALL OF THE TSUNAMI SOURCES NOW

Please check all of the output text files
Please plot all of the free surface shapes
You can decide to redo all tsunami sources

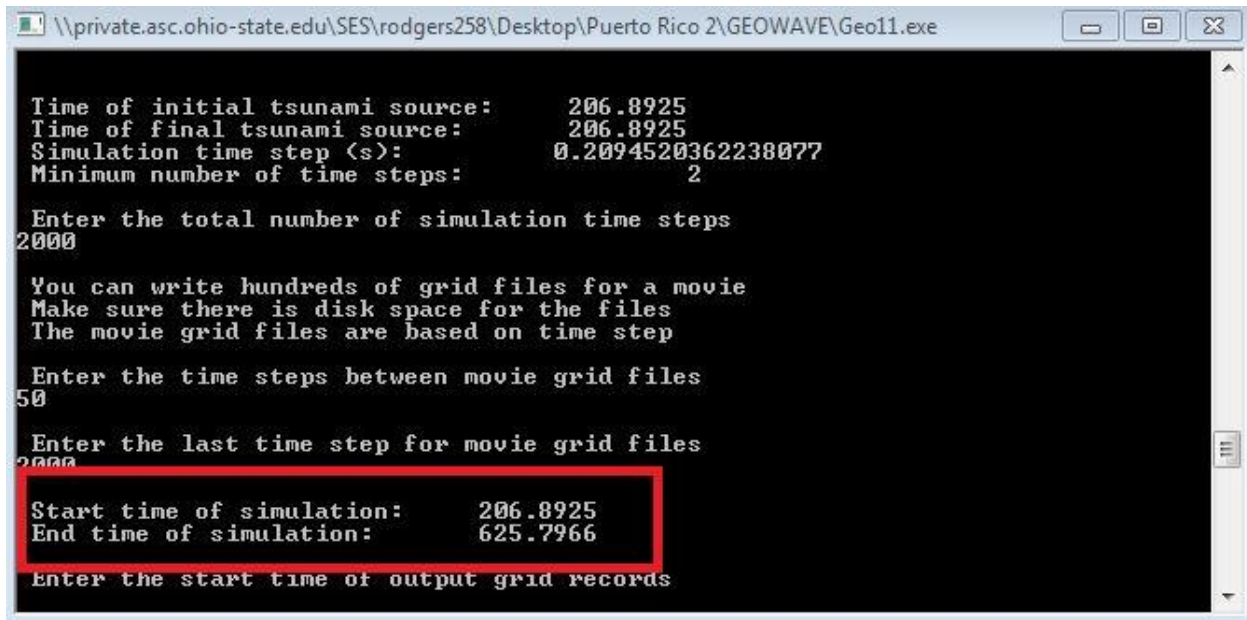
Type 0 if all tsunami sources are OK, 1 otherwise
0

Time of initial tsunami source:      206.8925
Time of final tsunami source:        206.8925
Simulation time step (s):             0.2094520362238077
Maximum number of time steps:         2

Enter the total number of simulation time steps
```

The last three lines of the output are highlighted with a red box.

120. In this case every step is equal to 0.2094520362238077 seconds. Keep this in mind when determining the total number of time steps. For example, 100 steps are just equal to 20.9 seconds of “real world” time.
121. Determine how long you need the wave to propagate for in the real world and divide that time by 0.2094520362238077 seconds to find the number of time steps needed. Enter that number and hit enter.
122. GEOWAVE will output ascii grids throughout the simulation. These show the current water height throughout the area at each time. Determine how long you would like the interval between these to be and divide by 0.2094520362238077 seconds to get the number of steps in that interval. Enter that number and hit enter.
123. It is possible to stop outputting these files before the simulation ends, to do this enter a number less than the total number of time steps. To have them output for the whole time, enter the total number of time steps.
124. GEOWAVE will also output wave information after the simulation. You can define the times it will collect data. To have it collect data for the whole simulation enter the times it provides above.



```
\\private.asc.ohio-state.edu\\SES\\rodgers258\\Desktop\\Puerto Rico 2\\GEOWAVE\\Geo11.exe

Time of initial tsunami source:      206.8925
Time of final tsunami source:      206.8925
Simulation time step (s):          0.2094520362238077
Minimum number of time steps:      2

Enter the total number of simulation time steps
2000

You can write hundreds of grid files for a movie
Make sure there is disk space for the files
The movie grid files are based on time step

Enter the time steps between movie grid files
50

Enter the last time step for movie grid files
2000

Start time of simulation:      206.8925
End time of simulation:      625.7966

Enter the start time of output grid records
```

125. Enter -9999 for the missing data value.
126. Hit 0 to confirm the inputs and hit enter.
127. Enter a name for the output data text file.
128. The simulation will start. It can take a while depending on the number of time steps and the grid size.
129. Once the simulation is complete you can close GEOWAVE.
130. GEOWAVE will have created multiple files throughout the simulation. The ones used in this study are located in the Movie and Grid folders created earlier.
131. The Movie files are the grids that were output during the simulation that give water height at each cell.
132. Before you can view these you need to replace the header with the original ESRI version.
133. Open the file that you saved of the original header and copy the 6 rows. Open one of the movie files and select the 5 rows of the header. Paste the original header and save. You must do this for any grid you wish to view.
134. The other file used in this study is the zmax file in the Grid folder. This gives the maximum height recorded by every cell through the entire simulation. Again, you must replace the header for this as well.